Receive Sensitivity Characterization of the PolySat Satellite Communication System

A Thesis Presented to the

Electrical Engineering Department Faculty of

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

Of the Requirements for the

Master of Science Degree in Electrical Engineering

By

Ivan M. Bland

March 2010

© 2010
Ivan M. Bland
ALL RIGHTS RESERVED

COMMITTEE MEMBERSHIP

TITLE:	Receive Sensitivity Characterization of the PolySat Satellite Communication System
AUTHOR:	Ivan M. Bland
DATE SUBMITTED:	March 2010
COMMITTEE CHAIR:	Dennis Derickson, Dr.
COMMITTEE MEMBER:	Jordi Puig-Suari, Dr.
COMMITTEE MEMBER:	Bryan Mealy, Dr.

ABSTRACT

Sensitivity Characterization of the PolySat Satellite Communication System

Ivan M. Bland

Following the successful launch of CP3 and CP4, the PolySat team noticed an unreliable uplink to both satellites. A significant problem with the PolySat COMM system is poor receive sensitivity of the communications system. Efforts have been made to improve the uplink margin, but without proper characterization of the receiver sensitivity, the problem cannot be fully addressed. By developing an accurate method of measuring receive sensitivity, a methodical approach can be used to properly diagnose the communication system and link budget. Two revisions of the PolySat COMM system will be measured and compared. An in-depth study of the PolySat COMM system will be performed, providing an interesting look at possible causes of the inconsistent uplink and methods of improving the COMM system. For future bus development, this test setup can be used to accurately measure the receive sensitivity.

ACKNOWLEDGEMENTS

Thanks to my family and friends for the unwavering support throughout my academic career.

Thanks to Dennis Derickson for his support and expertise. His guidance played a huge role in the work presented throughout this paper.

Thanks to Dr. P, for helping pioneer the CubeSat standard, and encouraging both PolySat and CubeSat to dream big.

Thanks to the PolySat team for support during testing, especially the software team for the constant troubleshooting of the software.

TABLE OF CONTENTS

LIST OF FIGURES ..... **IX**

LIST OF TABLES ..... **XIII**

LIST OF EQUATIONS ..... **XV**

CHAPTER 1. INTRODUCTION: SCOPE OF THESIS **1**

CHAPTER 2. BACKGROUND: OVERVIEW OF SATELLITE PROGRAM **3**

2.1 CUBESAT 3
2.1.1 Cal Poly CubeSat *4*
2.1.2 CubeSat Launch History *4*
2.2 POLYSAT PROGRAM 5
2.3 SATELLITES 5
2.3.1 CP1 ..... *6*
2.3.2 CP2 ..... *6*
2.3.3 CP3 ..... *8*
2.3.4 CP4 ..... *8*
2.3.5 CP5 ..... *9*
2.3.6 CP6 ..... *9*
2.3.7 CP7 ..... *10*
2.3.8 Lightsail-1 ..... *12*

CHAPTER 3. COMMUNICATION PROBLEMS **13**

3.1 UNRELIABLE UPLINK 13
3.1.1 Inability to Communicate with Satellites *13*
3.1.2 Downlink *14*
3.2 RECEIVE SENSITIVITY 14
3.2.1 Antenna Reciprocity *14*
3.2.3 Previous Receive Sensitivity Testing *15*
3.2.3 Link Budget – Uplink *17*
3.2.4 Link Budget – Downlink *18*
3.3 ADDRESSING THE UNRELIABLE UPLINK 19
3.3.1 Preview of Results – Receiver Sensitivity Testing *19*
3.3.2 Additional Testing Performed and Problems Discovered *20*
3.3.3 Documentation of the Sensitivity Measurement Setup Design and Testing Performed *21*

CHAPTER 4. MEASURING RECEIVE SENSITIVITY **22**

4.1 OVERVIEW 22
4.2 TEST SETUP COMPONENTS 23
4.3 RF SOURCE 26
4.4 ATTENUATION STAGE 27
4.5 RESISTIVE POWER SPLITTER 28
4.6 LOW NOISE AMPLIFIER 29
4.6.1 Design of Low Noise Amplifier *30*
4.6.2 Input Return Loss of LNA *33*
4.6.3 Output Return Loss of LNA *35*

4.6.4 Forward Gain of LNA *35*
4.6.5 Reverse Gain of LNA *37*
4.6.5 1 dB Compression Point *37*
4.6.6 Noise Figure of LNA *39*
4.7 HP8566A SPECTRUM ANALYZER 41
4.8 FARADAY CAGE 43
4.8.1 Screen Rooms *44*
4.8.2 Custom Faraday Cage *48*
4.8.3 Construction *49*
4.8.4 Features *51*
4.8.5 Attenuation Performance of Faraday Cage *54*
4.9 OTHER CONSIDERATIONS 55
4.9.1 RF Leakage *55*
4.9.2 Yaesu Radio RF Output Power *56*
4.10 SENSITIVITY MEASUREMENT SETUP CHARACTERIZATION 56
4.11 TEST SETUP – MEASURING SENSITIVITY OF THE POLYSAT COMM SYSTEM 59

CHAPTER 5. SENSITIVITY TESTING 64

5.1 POLYSAT SATELLITE COMM SYSTEM 64
5.1.1 Overview of COMM Setup *64*
5.1.2 CC1000 UHF Transceiver *65*
5.1.3 Receive Sensitivity versus Frequency Separation and Data Rate *66*
5.1.4 RSSI Output *68*
5.4.3 CDH Revision 4 ..... *69*
5.4.4 CDH Revision 5 ..... *69*
5.2 COMM SENSITIVITY TESTING 70
5.2.1 Overview of Testing *70*
5.2.2 CDH Testing – Measuring the Receive Sensitivity *71*
5.2.3 CDH Rev 4 – Measured Sensitivity Testing *71*
5.2.4 CDH Rev 5 – Measured Sensitivity Testing *72*
5.2.5 CP5 CDH Flight Candidate *74*
5.2.7 Yaesu FT-847 Transceiver *75*

CHAPTER 6. ADDITIONAL TESTING 78

6.1 RECEIVER NOISE FLOOR COMPARISON 78
6.1.1 Receive Line of CC1000 – Noise Floor at RX/TX Frequency *82*
6.1.2 Receive Line of CC1000 – Broadband Noise Floor *85*
6.1.3 Receive Line of CC1000 – Noise Floor over 70 CM Amateur Band *88*
6.1.4 Receive Line of CC1000 – Noise Floor Characteristics *89*
6.2 TESTING FOR REDUCED COMM SENSITIVITY FROM SWITCHING NOISE 90
6.2.1 Switching Noise from DC-DC Converters *90*
6.2.2 Switching Noise from I^2C Bus *92*
6.3 ADDITIONAL ISSUES RELATING TO INCONSISTENT UPLINK 93
6.3.1 Observations from CP3 and CP4 ..... *93*
6.3.2 Observations from Sensitivity Testing *93*
6.3.3 Long Duration Communication Test *95*

CHAPTER 7. RESULTS OF SENSITIVITY TESTING 98

7.1 COMPARISON OF COMM SENSITIVITY 98
7.1.1 Overall COMM Performance *98*
7.1.2 CC1000 Performance *98*
7.1.3 PolySat COMM Performance Compared to Future Replacement Transceiver *99*
7.2 RECOMMENDATIONS FOR IMPROVING UPLINK AND FUTURE POLYSAT COMM 99
7.2.1 Improved Layout of CDH Rev 5 ..... *100*
7.2.2 COMM Software Testing *100*
7.2.2 Temperature Controlled Crystal Oscillator *100*

7.2.3 Proper Testing Procedures to Verify the RF Chain *103*
7.2.5 U.FL Connector Problems *105*
7.2.4 Contract Manufacturing of Assembled boards *108*
7.2.6 High Frequency Probe *108*

CHAPTER 8. SUMMARY 110

8.1 RECEIVE SENSITIVITY TEST SETUP 110
8.1.1 Sensitivity Characterizations *110*
8.2 CDH SENSITIVITY PERFORMANCE 110
8.2.1 CDH Rev 4 versus Rev5 ..... *110*
8.2.2 Noise Characterization of the Receive Line *111*
8.2.3 Link Budget Compared to Receive Sensitivity of CDH Rev 5. ..... *111*
8.3 CC1000 111
8.3.1 Limitations of the CC1000 ..... *111*
8.3.2 Overall Sensitivity *113*
8.4 FUTURE WORK 113
8.4.1 New Layout for CP5 ..... *113*
8.4.2 Receive Sensitivity versus Temperature *114*
8.4.3 Antenna Characterization and Re-design *114*
8.4.4 Long Duration Testing *114*
8.4.5 Upgrading the Ground Station to Improve Uplink to the Satellite *115*
8.5 SUMMARY 116
8.5.1 Conclusion *116*
8.5.2 Final Words *116*

CHAPTER 9. WORKS CITED 118

APPENDICES

APPENDIX A: SENSITIVITY MEASUREMENT PROCEDURE 120
APPENDIX B: LIST OF ACRONYMS 128

LIST OF FIGURES

Figure 1 - CubeSat Standard: 10x10x10 cm cube, 1.33 kg maximum weight 3
Figure 2 - PPOD on left, 3 CubeSats on right..... 4
Figure 3 - CP1 satellite 6
Figure 4 - CP2 Flight unit 7
Figure 5 - CP3 Flight unit 8
Figure 6 - Engineering unit of CP6 in the cleanroom. 10
Figure 7 - CP7 development platform: particle damper beams on left, high voltage board for driving piezo crystals on right [12]. Both boards interface to a modified CDH and EPS..... 11
Figure 8 - John Abel, shown left, flying the CP7 development platform on the NASA Zero Gravity Flight. Three particle dampers were tested, driven with different amplitudes and frequencies. 12
Figure 9 - Antenna Reciprocity..... 14
Figure 10 - Field testing of CP6. The satellite was taken halfway up Bishop's Peak, approximately 2 miles away. Attenuators were placed on the ground station, reducing the signal strength. 16
Figure 11 – Link budget. Using typical orbital parameters and the above figure to calculate the slant range, the Friss Free Space equation determines the attenuation from path loss. The attenuation of the orbital path varies between 142.2-153.1 dB. 17
Figure 12 - System level overview of the setup developed used to measure the receive sensitivity of the PolySat COMM system..... 24
Figure 13 - Sensitivity Measurement setup: this shows all the necessary components required for measuring sensitivity. This setup was used to measure the sensitivity of two revisions of the PolySat COMM system and the ground station receiver. 26
Figure 14 - Attenuation Setup allowing signal strength to be adjusted from 0 to -110 dBm 27
Figure 15 - The resistive power splitter divides the signal equally to both the DUT and Spectrum Analyzer..... 28
Figure 16 - ZFRSC-42-S+ Power Splitter. Signals 6 dB down from the original signal (at port S) will appear at ports 1 & 2. With signals of equal magnitude reaching the Spectrum Analyzer and the DUT, the signal strength at the DUT is easily measured. 29
Figure 17 - Low Noise Amplifier used to increase sensitivity of the Spectrum Analyzer. The resistive splitter divides the RF path, and the Spectrum Analyzer is used to measure the amplitude of the signal reaching the satellite in the Faraday Cage..... 30
Figure 18 - Schematic of the custom built LNA..... 31
Figure 19 - Construction of LNA..... 32
Figure 20 - Miniature Faraday Cage surrounding LNA 32
Figure 21 - S_{11} of LNA 34
Figure 22 – S_{22} of LNA..... 35
Figure 23 - Forward Gain S_{21} of LNA..... 36
Figure 24 - Reverse Gain S_{12} of LNA..... 37
Figure 25 - The test setup used to measure the Noise Figure of the Low Noise Amplifier [22]..... 39
Figure 26 - Measured noise figure over the 430-450 MHz range..... 41

Figure 27 - The Noise Figure of the cascaded system (LNA and the Spectrum Analyzer) approaches the Noise Figure of the first stage of the cascaded system (LNA). This increases the sensitivity of the Spectrum Analyzer. 42
Figure 28 - Noise Figure F of the two stage cascaded system (LNA and Spectrum Analyzer)..... 42
Figure 29 - The screen room in RM 116..... 44
Figure 30 - Screen room in RM 118 (left) and accompanying RF passthrough (right)..... 45
Figure 31 - EMC Chamber at the RFID lab in Building 4..... 46
Figure 32 - Testing each screen room for isolation: a handheld radio transmitting at 437 MHz was placed outside each screen room, and the HP8566A Spectrum Analyzer with antenna was used to measure the power with the screen room door open and closed. The difference in measured power with the screen room door open and closed provided an approximate level of attenuation..... 47
Figure 33 - Concept of Faraday Cage construction 49
Figure 34 - Unetched PCB being soldered together to form the enclosure 50
Figure 35 - Completed cage, using clamps to seal the lid. Coax is seen attached to each RF pass-through 51
Figure 36 - Spacious interior allows testing on larger satellites (3U) if necessary. CP3 TestSat is attached via the U.FL antenna connector, with CDH Rev 5 (with the LNA amplifier, same CDH flown on CP6)..... 52
Figure 37 - N-Type and SMA pass-through ports. When not in use, each port should be terminated with a 50Ω termination to prevent the possibility of leakage. 52
Figure 38 - SMB Connectors used to pass DC power into the Faraday Cage 54
Figure 39 - Testing the Faraday Cage for isolation. A handheld radio was placed inside the cage, transmitting at 437 MHz. The HP8566A Spectrum Analyzer equipped with an antenna was used to measure the signal strength with the cage closed and open. The difference between these two measurements provides an approximate level of isolation. 54
Figure 40 - Characterizing the receive sensitivity setup 57
Figure 41 - Actual signal reaching DUT (dBm) versus attenuator setting. The attenuation was adjusted from 40 to 110 dB, and the signal reaching the Faraday Cage (Section E of Figure 12) was measured using the Spectrum Analyzer (Section D of Figure 12). A strong linear response indicates that the test setup (Figure 12) is capable of accurately measuring receive sensitivity. 58
Figure 42 - Sensitivity Measurement setup during a satellite response to a command. The PolySat COMM system (Section E) outputs 1W (+30 dBm) and the resistive splitter (Section C) only offers 6 dB port to port isolation. A signal of +24 dBm will permanently damage the LNA attached to the Spectrum Analyzer (Section D). 60
Figure 43 - Sensitivity setup for finding the threshold of sensitivity of the PolySat COMM system. The LNA is disconnected from the power splitter because the satellite response exceeds the maximum input power of the LNA and would cause permanent damage. 61
Figure 44 - Sensitivity test of the PolySat COMM system. The sensitivity threshold is -100.7 dBm, corresponding to the last successfully decoded command (indicated by a satellite response). 62
Figure 45 – Sensitivity measurement after the threshold of sensitivity is found. The LNA is used to verify the signal strength of the Minimum Detectable Signal (MDS), which is

the weakest signal the PolySat COMM system is capable of responding to. This is the measured receive sensitivity and is accurate to +/-2 dB. 63
Figure 46 - Main components of the redundant COMM system. CC1000 Transceiver on left, with RF amplifier on right. Most of the additional components are supporting circuitry for the transceiver and amplifier (matching, power decoupling, etc). Each redundant COMM is labeled A and B. 64
Figure 47 - High level circuit diagram of the CC1000 65
Figure 48 - CC1000 RSSI pin voltage versus receive power. This is a graph from the CC1000 datasheet, providing a reference voltage as a function of received signal strength..... 68
Figure 49 – RF Chain of CDH Rev 4. The antenna connector is AC coupled to the main RF switch, which selects COMM A or B. Individual RF switches select between RX and TX. The RX line goes directly to the CC1000, and the TX is from the RF amplifier output. 69
Figure 50 – RF Chain of COMM A on CDH Rev 5. The only difference is the addition of an LNA, associated matching network, and high-pass filter. 70
Figure 51 – CP5 Flight Candidate RSSI curve 75
Figure 52 - Test Setup to measure the receive sensitivity of the Yaesu FT-847 ground station receiver. The satellite is set to transmit every 30 seconds, providing the Yaesu FT-847 data packets to receive and decode. By adjusting the variable attenuator, the signal strength to the FT-847 was reduced until it could no longer decode packets, providing a threshold of receive sensitivity. 77
Figure 53 – Test setup to monitor the noise at the receive line of the PolySat COMM system. The LNA attached to the Spectrum Analyzer is used to observe the noise floor. 79
Figure 54 - Test setup showing the system noise floor of the LNA and Spectrum Analyzer. This is important in comparisons between the measured noise of each COMM system. 80
Figure 55 – LO leakage. For the CC1000 transceiver, the leakage is -57 dBm. 81
Figure 56 – The LO will be 150kHz above the RX frequency for high-side injection, and 150 kHz below RX for low-side injection. 81
Figure 57 - CDH R4 CommA noise floor, centered at the PolySat COMM receive frequency 437.365 MHz. LO leakage visible at 437.515 MHz. RBW 10 kHz. Crystal harmonic also visible. 82
Figure 58 - CDH R4 CommB noise floor, centered at the PolySat COMM receive frequency 437.365 MHz. LO leakage visible at 437.515 MHz. RBW 10 kHz 82
Figure 59 - CC1000 Development Board, centered at receive frequency 434.010 MHz. LO Leakage visible at 433.860 MHz, RBW 10 kHz 83
Figure 60 - System Noise Floor of the LNA and Spectrum Analyzer. RBW 10 kHz. The input of the LNA is terminated with a 50 Ω connection. This provides a reference noise level at which to compare each noise floor graph to. 83
Figure 61 - CDH Rev 5, CommA, centered at receive frequency 436.365 MHz, RBW 10 Khz 84
Figure 62 - CDH Rev 5, CommB, centered at receive frequency 437.365 MHz, RBW 10 kHz 84
Figure 63 - CDH Rev 4 CommA, 100-500 MHz, RBW 1MHz. Harmonics of crystal spaced 14.74 MHz apart are clearly visible. Broadband noise is much higher than CC1000 development board (Figure 67) 85

Figure 64 - CDH Rev 4 COMMB, 100-500MHz, RBW 1MHz. Harmonics of crystal spaced 14.74 MHz apart are clearly visible. Broadband noise is much higher than CC1000 development board (Figure 67) 86
Figure 65 - CDH Rev 5 CommA, frequency span of 100-500 MHz, RBW 1MHz. 86
Figure 66 - CDH Rev 5, COMMB, frequency span of 100-500MHz, RBW 1MHz 86
Figure 67 - CC1000 Development Board, 100-500 MHz, RBW 1MHz. Crystal harmonics repeated every 14.74 MHz, and LO leakage visible at 433.860 MHz 87
Figure 68 - System Noise Floor 100-500 MHz, RBW 1MHz (LNA and Spectrum Analyzer)..... 87
Figure 69 - CDH Rev 4, COMMA, RBW 100kHz, over the 70 CM amateur band..... 88
Figure 70 - CDH Rev 4, COMMB, RBW 100kHz, over the 70 CM amateur band..... 88
Figure 71 - CC1000 Development board, RBW 100kHz, over 70 CM amateur band 89
Figure 72 - System Noise Floor, over 70 CM amateur band 89
Figure 73 – The CDH Rev 4 had two types of crystal harmonics visible. The larger harmonic is spaced 14.74 MHz apart (the frequency of the CC1000 crystal) and the smaller harmonics were spaced every 1.474 MHz 89
Figure 74 - The DC-DC converter regulates the battery voltage from 4.2V to 3V for the PolySat COMM System [2]. 90
Figure 75 - I^2C switching (SCL_CDH_2) and data line (SDA_CDH_2) originate from the CDH processor [3]. 92
Figure 76 - Beacon commands sent every 60 seconds, and the satellite responses monitored. The horizontal axis shows how many satellite responses there were for each command from the group station. The vertical axis is divided into bins, showing that not every command received a response..... 95
Figure 77 - Variations of the IF due to the crystal can cause a reduction in the sensitivity of the CC1000 102
Figure 78 - RF Chain testing of CDH Rev 5. Using the RF source, a signal at 437 MHz was applied to the antenna connector. The CC1000 is not receiving any signal through the antenna connector, indicating a manufacturing defect in the RF chain. 104
Figure 79 - Male U.FL connector on CDH Rev 5 105
Figure 80 - U.FL female connector with open circtuit defect (center conductor prongs are spaced too far apart) shown on left, new U.FL connector shown on right. The connector on right shows the proper center pin spacing..... 106
Figure 81 – A worn-out U.FL connector, on left, behaves an open circuit. By adjusting the spacing of the two prongs, a proper connection was established, shown on right..... 106
Figure 82 - Frequency separation 112
Figure 83 - HVL-1100 1000W amplifier..... 115

LIST OF TABLES

Table 1 - Uplink Budget 18
Table 2 - Downlink Budget..... 19
Table 3 - Measured sensitivities of two revisions of the PolySat COMM system and the ground station receiver..... 20
Table 4 - Variable Attenuator Characteristics 27
Table 5 - Characteristics of ZFRSC-42-S+ Power Splitter..... 28
Table 6 - LNA Specifications: required voltage bias, typical operating current, and absolute maximum power..... 33
Table 7 - S_{11} across the 70 CM Amateur Radio band..... 34
Table 8 - S_{22} of LNA..... 35
Table 9 – S_{21} across the 70 CM Amateur Radio band..... 36
Table 10 – S_{12} across the 70 CM Amateur Radio band..... 37
Table 11 - 1 dB compression point of LNA (output)..... 38
Table 12 - Typical and measured Noise Figures from 0.010-3 GHz..... 40
Table 13 - Noise Figure and Gain of individual stages in dB and linear equivalents, used to calculate the Noise Figure of cascaded Spectrum Analyzer and LNA. 43
Table 14 - Comparison of the attenuation of each Screen Room. Each room does not provide enough isolation at UHF. 47
Table 15 - Variables affecting skin depth of material..... 48
Table 16 - Feedthrough capacitors capable of passing DC power. Ground clips soldered to cage. 53
Table 17 - Comparison of attenuation of each screen room to the custom built Faraday Cage. The cage offers 10 dB more isolation, which was enough to isolate the satellite from stray radiation. 55
Table 18 – CC1000 receive sensitivity is a function of frequency, data format, data rate, and frequency separation [8]. This table is obtained from the CC1000 datasheet. The red highlighting indicates that the uplink to the CC1000 is 600 baud data rate. 67
Table 19 – The measured sensitivity of CDH Rev 4 for both COMMA and COMMB, tested using the sensitivity measurement setup in Section 4.11 71
Table 20 –Resting RSSI of CC1000 of CDH Rev..... 72
Table 21 - RSSI Characterization of CDH Rev 4..... 72
Table 22 - Sensitivity of CDH Rev 5 (with preamp), tested using the sensitivity measurement setup in Section 4.11..... 73
Table 23 - Resting RSSI of CDH Rev 5 73
Table 24 - RSSI from both COMMS of CDH Rev 5 compared to datasheet. 74
Table 25 - CP5 Flight Candidate, receive sensitivity performance 74
Table 26 - CP5 Flight Candidate, resting RSSI values..... 75
Table 27 – Results of the noise measurement at the RX frequency of CDH Rev 4 and CC1000 development board. The noise of COMMA at the RX frequency is 10 dB greater than the CC1000 development board, and 5 dB higher than COMMB, possible causing the difference in measured sensitivity between COMMA and COMMB..... 83
Table 28 – Results of the noise measurement at the RX frequency of CDH Rev 5 and CC1000 development board. The noise of COMMA at the RX frequency is 20 dB greater than COMMB, possible causing the difference in measured sensitivity between COMMA

and COMMB. The S_{12} of the LNA (Figure 50) is 30 dB, reducing the LO leakage (Section 6.1) and any noise between the output of the LNA and the input to the CC1000 (Figure 50) 84
Table 29 – Conclusions from the noise measurements of the receive line 88
Table 30 - Testing for differences in sensitivity caused by DC-DC converters. No significant difference in receive sensitivity is observed without the DC-DC converters, eliminating them as suspect in causing desensitization of the COMM system. 91
Table 31 - A list of four common satellite behavior problems observed during sensitivity testing 93
Table 32 - Long duration COMM test results 96
Table 33 - Overview of the performance of COMM tested for sensitivity 98
Table 34 – Sensitivity comparison of CC1000 and the AX5042 future replacement transceiver. The datasheet of the AX5042 states that the receive sensitivity is not dependent on FSK frequency separation [17] 99
Table 35 - Total variation of crystal over a large temperature range, calculated from application note AN019 available from Texas Instruments 101
Table 36 - Resulting IF error, caused by temperature variations 101
Table 37 - A list of possible ways to mitigate open circuit failure of the female U.FL connector 107
Table 38 - Measured receive sensitivities of CDH Rev 4, Rev 5, and the PolySat ground station receiver 110

LIST OF EQUATIONS

Equation 1 - Calculating the free space path loss 17
Equation 2 - Noise Figure 39
Equation 3 - Calculated Noise Figure of the Low Noise Amplifier 39
Equation 4 - Calculated Noise Figure of the Spectrum Analyzer 41
Equation 5 - Noise Figure of the Spectrum Analyzer and the LNA cascaded together 43
Equation 6 - Skin depth formula 48
Equation 7 – Calculating the skin depth of copper of a 437 MHz signal 48
Equation 8 – Equation used to calculate Percent Error 58
Equation 9 – Calculating the expected receive sensitivity of the Yaesu FT-847. The datasheet states that the minimum sensitivity is 0.125 µV, so the minimum sensitivity in power (dBm) can be calculated 76
Equation 10 - Calculating the thermal noise of the Yaesu FT-847 receiver in Single Side Band (SSB) 76

Chapter 1. INTRODUCTION: Scope of Thesis

This paper will specifically address the characterization of receive sensitivity of the PolySat COMM system. With increasingly demanding payloads on CubeSats, a reliable COMM system is of the utmost importance. By developing a method of testing receive sensitivity, different revisions of the PolySat COMM system can be specifically measured and compared to the expected sensitivity. Receive sensitivity problems (caused by desensitivity, poor layout, transceiver interfacing or software problems, etc) can be discovered early in the development process rather than after satellite development and launch. The performance of flight candidate boards can be directly compared before building flight unit satellites for launch.

Chapter 1 discusses the scope of this paper and outlines the goals of the thesis.

Chapter 2 provides the reader with a background of the CubeSat program, and an overview of Cal Poly's PolySat program. Cal Poly's satellites and current projects are briefly described.

Chapter 3 outlines the motivation for receive sensitivity. Evidence of poor receive sensitivity is described. The link budget for a successful uplink is discussed, giving the reader an idea of what sensitivity is necessary for a successful uplink. Previews of the sensitivity testing results are included, providing the reader with a quick look at the conclusions achieved. This chapter serves to set the stage for an in-depth discussion of the characterization that follows.

Chapter 4 describes the test setup developed to measure the receive sensitivity. A discussion of the entire system provides the reader with a detailed analysis of the components of the test setup. The difficulties of measuring receive sensitivity are also discussed. A procedure for executing a receive sensitivity test can be found in the appendix.

In Chapter 5, Cal Poly's COMM systems are measured for receive sensitivity. The first setup, CDH Rev. 4, is the COMM system flown on CP3 and CP4. CDH Rev. 5 includes a Low Noise Amplifier (LNA), and was flown on CP6. For a baseline comparison, the Yaesu FT-847 ground station transceiver is measured for sensitivity.

Chapter 6 discusses additional testing performed, in order to further investigate possible causes of poor sensitivity.

Chapter 7 provides observations and test results of each COMM system tested. Comparisons of each receive sensitivity are made, and possible methods of increasing receive sensitivity are discussed.

Chapter 8 concludes the thesis with conclusions and recommendations for future work in the area of receive sensitivity.

Chapter 2. Background: Overview of Satellite Program

2.1 CubeSat

The CubeSat standard was developed as a joint project between Stanford University's Space Systems Development Laboratory and Cal Poly's Multi-disciplinary Space Technologies Laboratory. Stanford professor Bob Twiggs and Cal Poly professor Dr. Jordi Puig Suari led the way, and now Cal Poly's CubeSat program maintains the specifications for the 10x10x10 cm satellites [3]. CubeSat developers, such as other universities or corporations, must adhere to the 1.33 kg mass limit and dimensions of a 10cm cube. Other specifications, such as the Remove Before Flight (RBF) pin, diagnostic port location, and deployment switches, are contained in the specification document.

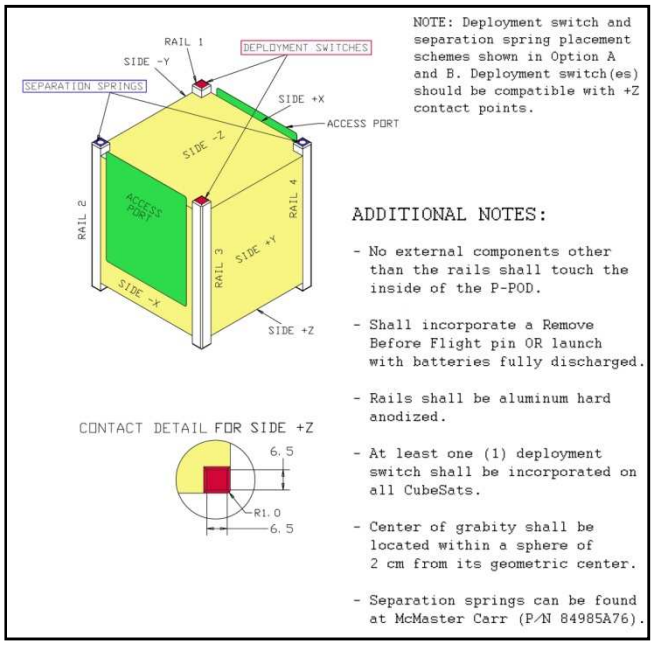

RAIL 1
DEPLOYMENT SWITCHES
SIDE -Y
SEPARATION SPRINGS
SIDE +X
ACCESS PORT
SIDE -Z
RAIL 2
ACCESS PORT
RAIL 4
RAIL 3
SIDE +Y
SIDE -X
SIDE +Z
NOTE: Deployment switch and separation spring placement schemes shown in Option A and B. Deployment switch(es) should be compatible with +Z contact points.
ADDITIONAL NOTES:
- No external components other than the rails shall touch the inside of the P-POD.
- Shall incorporate a Remove Before Flight pin OR launch with batteries fully discharged.
- Rails shall be aluminum hard anodized.
- At least one (1) deployment switch shall be incorporated on all CubeSats.
- Center of grabity shall be located within a sphere of 2 cm from its geometric center.
- Separation springs can be found at McMaster Carr (P/N 84985A76).
CONTACT DETAIL FOR SIDE +Z
6.5
R1.0
6.5

Figure 1 - CubeSat Standard: 10x10x10 cm cube, 1.33 kg maximum weight

2.1.1 Cal Poly CubeSat

In addition to maintaining the CubeSat standard, Cal Poly's CubeSat program designs and manufactures the Poly Picosatellite Orbital Deployer (P-POD), which interfaces to the launch vehicle and deploys up to three CubeSats into orbit. Launch provider coordination and satellite integration is also led by CubeSat.

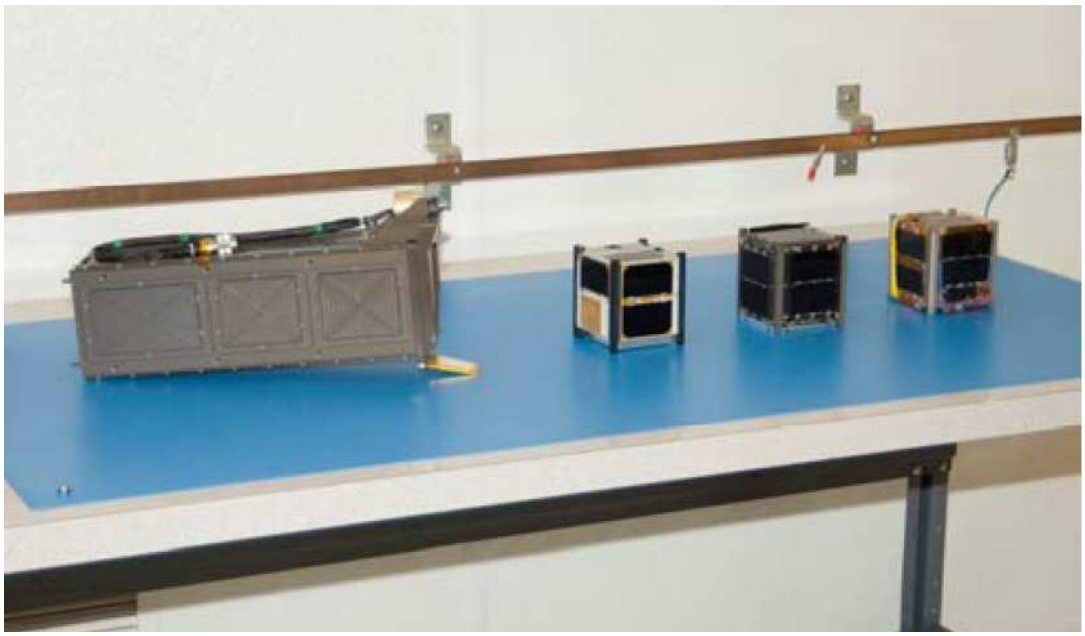


Figure 2 - PPOD on left, 3 CubeSats on right.

2.1.2 CubeSat Launch History

Eurockot 2003 – First CubeSat launch. Two Cal Poly Mk. I P-PODs successfully deployed four CubeSats.

Dnepr 1 2006 – Five Mk. II P-PODs with fourteen CubeSats were lost due to launch vehicle failure.

Minotaur I (TacSat2) 2006 – One modified Mk. II P-POD deployed GeneSat-1, a NASA Ames CubeSat.

Dnepr 2 2007 – Three Mk. II P-PODs successfully launch seven Cubesats, including Cal Poly's CP3 and CP4.

Falcon-1 2008 – Two modified Mk. III P-PODs with two NASA 3U CubeSats were lost due to launch vehicle failure.

Minotaur I (TacSat3) 2008 – Two P-PODs launched four CubeSats, including Cal Poly's CP6.

2.2 PolySat Program

PolySat, Cal Poly's CubeSat development program, is a team of multidisciplinary students designing CubeSats for Cal Poly. Both PolySat and CubeSat teams are located in the ATL (Advanced Technologies Laboratory) Building 007 Room 15. Originally founded in 1999, the PolySat team embraces Cal Poly's "Learn by doing" motto by developing satellites from the ground up. Although CubeSat subsystems are commercially available for purchase, such as COMM or power systems, PolySat emphasizes the student learning experience by developing all hardware and software in house.

Located in Room 15 Building 7, the lab provides the team with the necessary tools for satellite development: electronics bench for hardware development and RF testing, a software bench with computers, and two independent ground stations for communicating with the satellites during passes. CubeSat maintains a cleanroom down the hall, used for satellite integration to the P-POD, and a Thermal Vacuum Chamber (TVAC) is located in Building 4.

2.3 Satellites

Over the years, PolySat has developed several satellites. Three of these are currently in orbit. PolySat is also currently involved in several projects.

2.3.1 CP1

Development of Cal Poly's first satellite, CP1, began in 2000. The payload included a sun sensor donated by Optical Energy Technologies, and a magnetic torquer (magnatorquer) embedded in a side panel [19]. Although the Dnepr launch vehicle failed, CP1 proved that a team of students with no satellite building experience could complete the entire cycle of satellite development. Additionally, the satellite was completely built with Consumer Off The Shelf (COTS) components. This is a typical characteristic of CubeSats to reduce development cost.

Figure 3 - CP1 satellite

2.3.2 CP2

CP2 marked Cal Poly's second satellite, and first attempt at standardizing the satellite bus. A satellite bus is the infrastructure of the satellite, encompassing all major systems: Command and Data Handling (C&DH), Electrical Power System (EPS), and the Communication System (COMM). Called the CP Bus, it consisted of the C&DH board, the EPS board, and side panels with solar cells. By standardizing the bus, payload development and integration would be easier. CP2 is considered the first version of the standardized CP Bus, and built upon the lessons

learned from CP1. The satellite bus contains all the major subsystems: communication system, command and data handling, power generation and storage, and the mechanical structure. The satellite payload is interfaced to the bus. For CP2, bus improvements include triple junction solar cells, dual 1950 mAh Li-Ion batteries, and Magnetorquers (attitude control performed by magnets generating a torque against the Earth's magnetic field) in each side panel. The C&DH featured a redundant COMM system, and an I^2C bus for data transfer [3]. A PIC microcontroller served as the brain. The EPS contains several "Smart Fuses" which are fuses designed to reset once a fault is cleared, protecting from single event failures. Independent DC-DC converters provide regulated voltage rails for each system [2]. To date, the current CP Bus is still based off this design, but with slight hardware revisions made to both C&DH and the EPS. Hardware revisions have ranged from simple (updating layout for new components) to system level improvement (adding a Low Noise Amplifier to the COMM) [4].

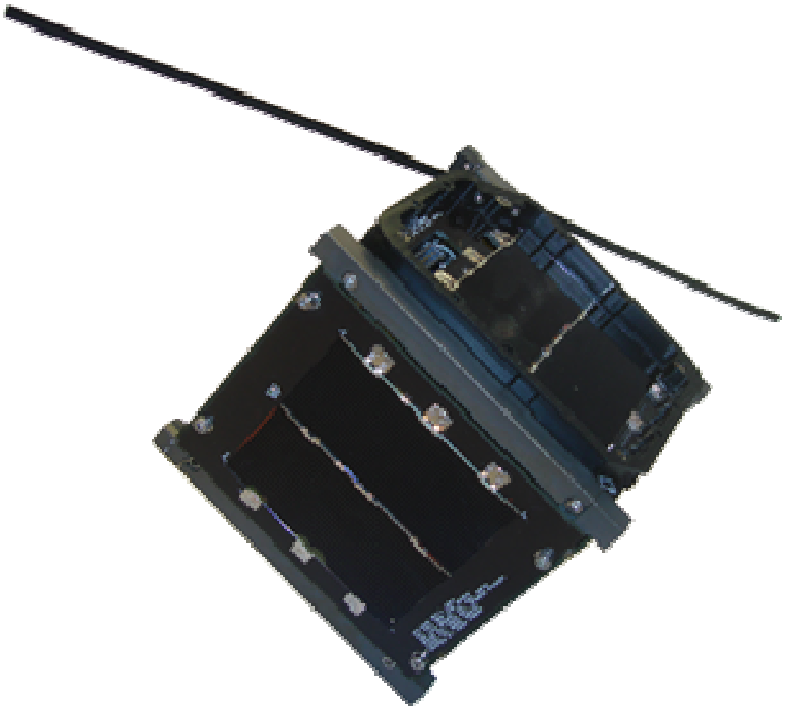


Figure 4 - CP2 Flight unit

Besides flight testing of the CP Bus, CP2 contained an energy dissipation experiment. CP2 never reached orbit due to the Dnepr 1 launch vehicle failure.

2.3.3 CP3

The primary mission of CP3 was attitude determination and control [19]. The side panels were equipped with 2-axis Magnetometers, allowing measurement of the Earth's magnetic field. Coils of wire embedded in the inner layers of the PCB served as Magnetorquers. By passing current through the coils, a magnetic field could be generated to torque against the Earth's magnetic field. CP3's payload also contained imaging sensors to photograph the Earth. CP3 was launched in 2007 on Dnepr2.

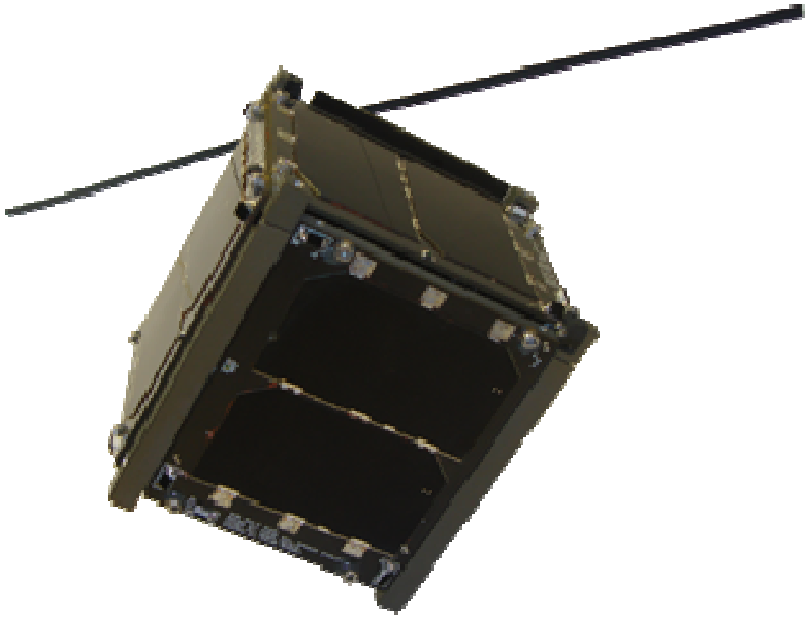


Figure 5 - CP3 Flight unit

2.3.4 CP4

After the failure of Dnepr 1, the backup flight unit of CP2 was re-flown on Dnepr 2. Although it is actually CP2, the flight required a unique name, resulting in a rename from CP2 to CP4. Several months in orbit, the satellite failed. The C&DH seems to be locked up, but the

satellite still switches between the redundant COMMs and will respond to a limited set of commands.

2.3.5 CP5

CP5, currently in the design phase, consists of a de-orbiting mechanism payload. Since CubeSats use Consumer Off-the-Shelf Components (COTS), the target lifetime is only 3-6 months. But CubeSats, typically in Low Earth Orbits (LEO) of approximately 500-700 km, will continue to orbit for 25-30 years as space debris. De-orbiting mechanisms will allow the CubeSat to re-enter and burn up in the Earth's atmosphere after completing the primary mission. Since CP5 will utilize the standard CP Bus, a goal of this thesis is to provide recommendations on bus improvement, specifically for improving uplink reliability.

2.3.6 CP6

After CP3 and CP4 were flown, the PolySat team noticed a significant problem in closing the uplink to both satellites. To combat the poor receive sensitivity of the CP Bus, a Low Noise Amplifier (LNA) was added between the antenna and receiver. A tri-state buffer was added between the payload processor and cameras to ensure data was being sent to only one of the two cameras at a time. Compared to CP3, the software received a major overhaul. Significant software changes included more efficient uplink commands, checksum value and error statistics of the I^2C bus, and the ability to pause the sensor snapshot circular buffer [23].

Figure 6 - Engineering unit of CP6 in the cleanroom.

Launched May 2009, CP6 is considered a huge success. More data was collected in the first few months from CP6 than the amount of data collected from CP3 in over a two year period. Uplink to the satellite was more consistent, suggesting that the LNA helped improve the receive sensitivity. Before satellite succumbed to a CDH hardware failure in September 2009, the team was successful in de-tumbling the satellite (reducing the spin rate) using its onboard attitude determination and control. This is accomplished by using magnetometers to measure the Earth's magnetic field, while coils of wire imbedded in the side panels can provide a torque against it. The team also demonstrated the ability to "spin up" the satellite, by reversing the process to increase the spin rate. Additionally, the team was able to turn on the payload and run a test to check the status of the payload. Several pictures were taken.

2.3.7 CP7

CP7, a particle damping experiment sponsored by Northop Grumman, is currently under development. Particle dampers consist of small metal cavities filled with tiny particles. In a

reduced or zero gravity environment, the particles would create a damping effect as the particles transfer momentum through frictional collisions [12]. Particle damper applications could involve reducing vibration in scientific equipment (such as optical systems) in a zero gravity environment. Modeling the performance of particle dampers in microgravity is difficult due to its non-linear behavior and dependence on gravity.

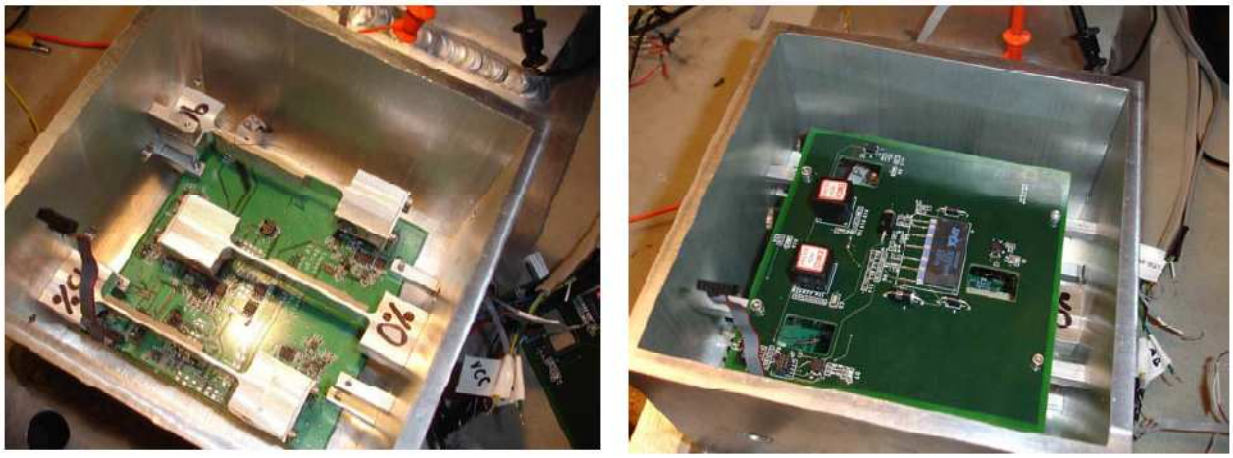


Figure 7 - CP7 development platform: particle damper beams on left, high voltage board for driving piezo crystals on right [12]. Both boards interface to a modified CDH and EPS.

The CP7 team, led by John Abel, developed an experiment that flew on the NASA Zero-G flight in June of 2009. The experiment consisted of cantilever beams with particle dampers, with piezo driving elements to vibrate the beams at different frequencies and amplitudes [12].

Figure 8 - John Abel, shown left, flying the CP7 development platform on the NASA Zero Gravity Flight. Three particle dampers were tested, driven with different amplitudes and frequencies.

2.3.8 Lightsail-1

The Planetary Society is developing a spacecraft propelled by sunlight. This is will be done by deploying a large sail, and photons hitting the sail will transfer energy to the spacecraft. Cal Poly will provide the electronics bus, including the CDH, EPS and COMM. Since Lightsail will be much more ambitious than previous missions, it is very important to determine the cause of the unreliable uplink to the PolySat COMM system.

Chapter 3. Communication Problems

3.1 Unreliable Uplink

3.1.1 Inability to Communicate with Satellites

After the successful launch of CP3 and CP4, the team experienced difficulty in sending commands to both satellites. The main motivation for the development of a reliable test setup is spurred by the team's unreliable uplink to CP3 and CP4. During operations, the team found it very difficult to get commands through, but very easy to receive data from the satellite. CP3 and CP4 pass over the PolySat ground station twice a day, and a typical window for communication is approximately 6-10 minutes. During this window, the team sends a command every 3-5 seconds, listening for a response between commands. This means that during a typical pass approximately 140-160 commands are sent. A good pass would be getting the satellite to respond to at least one command. Getting a command through is random, with no observable pattern. In some cases, the satellites would only respond once or twice in a two week period. The communications system was revised and a more consistent uplink was observed for CP6, but the uplink was still marginal. All three satellites show that the communication system is not adequate.

The poor uplink of the satellites in orbit is blamed on poor receive sensitivity of the CP Bus. Without measuring the receive sensitivity, the team lacks conclusive data on how well the COMM system is actually performing. By measuring the sensitivity and comparing it to the expected performance of the transceiver, an accurate statement of the COMM system's performance can be made. Further testing can identify causes of poor sensitivity, providing valuable information for developing a more robust COMM system.

3.1.2 Downlink

While the team found it very difficult to get commands through, the ground station could easily decode packets from the satellite, indicating the receive sensitivity of the ground station to be more than adequate.

3.2 Receive Sensitivity

Several observations support the theory that the CP Bus has poor receive sensitivity. Antenna reciprocity, successful downlink, and on-orbit data suggest that closing the uplink requires increasing sensitivity of the CP Bus.

3.2.1 Antenna Reciprocity

Antenna reciprocity states that the gain of an antenna will be the same in transmit and receive directions. If a communications link can be established between two antennas, due to antenna reciprocity, the communication can occur both ways. Either antenna can be the transmitter or receiver, regardless of differences between the two antennas.

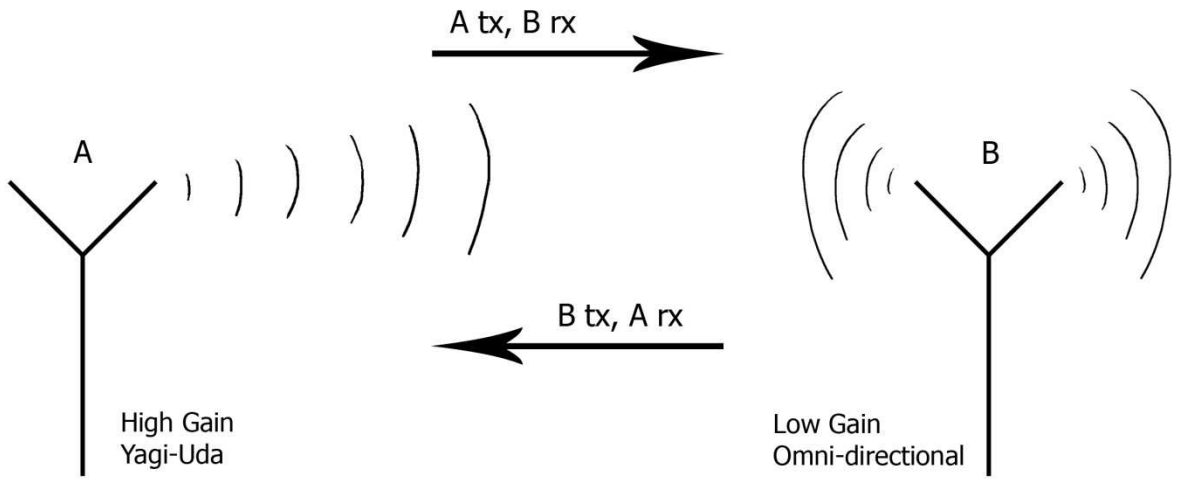


Figure 9 - Antenna Reciprocity

Using the Figure 9 to illustrate reciprocity, Antenna A is a high gain directional antenna. Antenna B is a low gain omni-directional antenna. With antenna A transmitting, the high gain provides a lot of power to antenna B. When antenna B transmits, the high gain of antenna A (due to reciprocity) allows easy reception of the signal. The system can also be described from antenna B's point of view. PolySat's ground station can easily decode data dumps from CP3 and CP4. If communication can occur one way, why is the uplink so difficult to close? Since successful downlink shows that the antenna system is more than adequate, this suggests the CP Bus receiver is much less sensitive than the ground station receiver. While this supports the theory of poor receive sensitivity, without an accurate measurement of both receivers' sensitivity, no conclusion can be made.

3.2.3 Previous Receive Sensitivity Testing

After the completion of the CP Bus for CP2, the team performed range testing to verify the performance of the COMM system. According the link budget, a satellite at around 2500 km will have a path loss of approximately 153 dB. The satellite was taken to a location 6 km away (approximately 100 dB attenuation), and the output of the ground station was attenuated by 50 dB [3]. While this test provides valuable information, it does not verify the CC1000 as capable of its stated receive sensitivity. This type of testing lacks a method of accurately determining the power reaching the satellite, providing little information about the sensitivity of the CC1000. Additionally, it is difficult to measure the power output of the ground station radio to verify the attenuation is reducing the signal to the desired level. RF leakage is possible, especially at greater power levels (over 10 dBm). This reduces the reliability of the testing performed. The magnitude of the signal reaching the satellite must be accurately measured to assess whether or

not the COMM system is capable of overcoming the path loss in orbit. It is also difficult to predict how multipath (signals reaching antenna via multiple paths, caused by reflections off terrain) affects the testing.

Following the addition of the LNA to the CP Bus, range testing was performed in a similar manner to verify the improvement in sensitivity [4]. Although a 10 dB improvement was observed, there were several problems with the testing procedures. Like the previous testing, attenuation was added to simulate the orbital path loss, but the test lacked a conclusive measurement of the actual output power of the ground station. The test also lacked a method of measuring the power received at the satellite. Using fixed attenuators in 3 and 10 dB increments reduced the resolution of the test. A variable attenuator could help resolve sensitivity improvement in greater detail, but a controlled method of feeding an RF signal to the satellite is lacking, which is needed to accurately measure the receive sensitivity.

Figure 10 - Field testing of CP6. The satellite was taken halfway up Bishop's Peak, approximately 2 miles away. Attenuators were placed on the ground station, reducing the signal strength.

3.2.3 Link Budget – Uplink

Using Derek Huerta's link budget calculator [3], the attenuation of the orbital path was calculated for both best and worst cases. Assuming a 700km 98 degree inclination as a typical CubeSat orbit, the satellite to ground station distance will be a function of the elevation from the horizon. For worst case, a 5 degree elevation results in a slant range of over 2,500 km. At 90 degrees (satellite passing directly overhead), the slant range is simply 700 km. Thus, the attenuation varies from 142.2 to 153.4 dB.

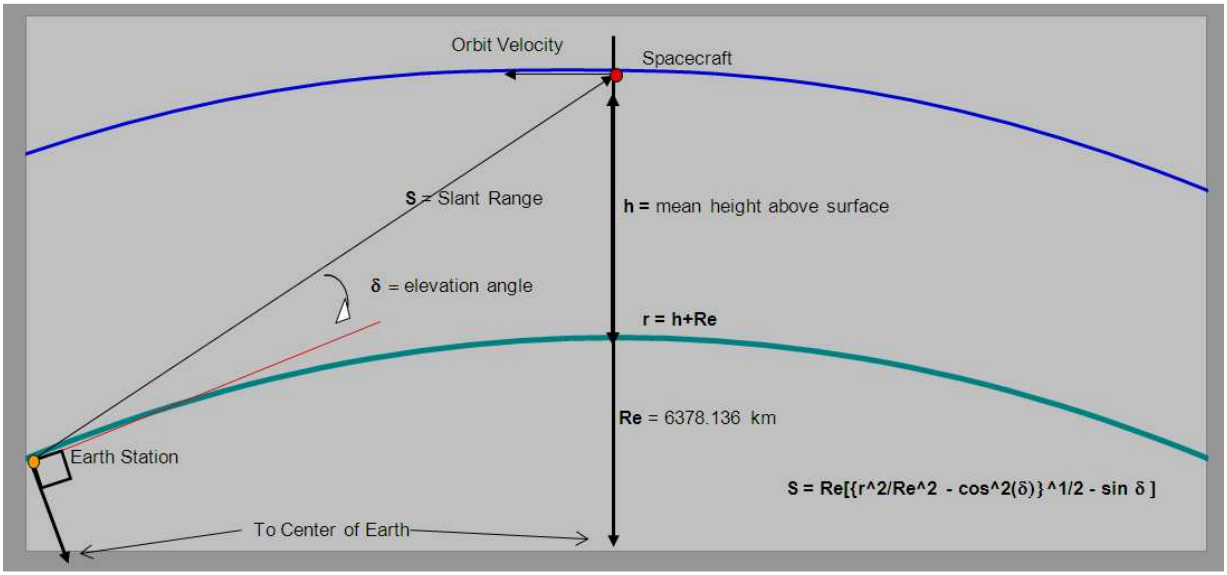


Figure 11 – Link budget. Using typical orbital parameters and the above figure to calculate the slant range, the Friss Free Space equation determines the attenuation from path loss. The attenuation of the orbital path varies between 142.2-153.1 dB.

$$\text{Path Loss (dB)} = 10\log_{10}\left[\left(\frac{4\pi df}{c}\right)^2\right] \qquad \begin{matrix}\text{d = distance (m), f = frequency (Hz)} \\ \text{c = 3.0 x } 10^2 \text{ (m/s)}\end{matrix}$$

Equation 1 - Calculating the free space path loss

The Hertz ground station, equipped with dual phased circular polarized Yagi antennas and a 100W amplifier, outputs approximately +72 dBm [6]. Subtracting off the path loss, the signal strength at the satellite will be between -71 to -83 dBm. The CP Bus antenna is a ½ λ

dipole, but with slightly shorter length due to size limitations. A characterization of the antenna showed the range of the E-Plane radiation pattern to vary -12 dB from the max depending on orientation [13]. An ideal dipole has a gain of 2.15 dBi (dB relative to isotropic), so an antenna gain of +2 to -10 dBi is a reasonable approximation.

Parameter	Magnitude	Comments
P_{TX} (Amplifier Output)	+50 dBm	100W
G_{ANT_TX} (Isotropic Antenna gain)	+18.95 dBi	16.8 dBd + 2.15 dB = 18.95 dBi
G_{PHS_TX} (Gain from dual phasing)	+3	Dual phased antennas provide additional gain
L_{TX} (5/8" hardline loss)	-0.22 dB	50 ft length
L_M (Miscellaneous loss)	-1 dB	Estimated additional loss (Connectors, radio, etc.)
L_{FS} (Free space path loss)	-142.2 to -153.4 dB	Actual distance to satellite varies during pass
G_{RX} (Antenna gain of satellite)	+2 to -10 dBi	Depends on orientation
Total	**-70 to -93 dBm**	Approximate strength after antenna (rounded)

Table 1 - Uplink Budget

A sensitivity of -103 dBm would provide a worst case margin of 10 dB. To ensure a reliable uplink the margin should be 20 dB. In the next revision bus, the AX5042 transceiver (chosen as the replacement for the CC1000) will provide much better sensitivity, allowing a greater margin. Increasing the ground station transmit power will also insure a greater degree of uplink margin. A receiver sensitivity of -103 to -113 dBm would provide a 10 to 20 dB worst case link margin.

3.2.4 Link Budget – Downlink

The downlink budget is an important reference for when the sensitivity of the ground station receiver is characterized.

Parameter	Magnitude	Comments
P_{TX} (Amplifier Output)	+30 dBm	RF amp produces 1W
G_{TX} (Isotropic Antenna gain)	+2 to -10 dBi	Depends on orientation
L_{FS} (Free space path loss)	-142.2 to -153.4 dB	50 ft length
L_M (Miscellaneous loss)	-1 dB	Estimated additional loss (Connectors, radio, etc.)
L_{RX} (5/8" hardline loss)	-0.22 dB	50 ft length

G_{RX} (Antenna gain)	+18.95 dBi	Antenna Gain
Total	**-90 to -113 dBm**	Approximate strength after antenna (rounded)

Table 2 - Downlink Budget

The antenna system has an SSB Electronics preamplifier before it reaches the Yaesu FT-847 transceiver, but this was not included in the link budget because it does not increase the sensitivity of the transceiver [6]. The preamplifier's purpose is to increase the signal after the antenna to overcome losses in the feedline to the transceiver. The ground station receiver must have a sensitivity of -123 dBm to provide a 10 dB worst case link margin.

3.3 Addressing the Unreliable Uplink

In order to shed light on the unreliable uplink problem, an accurate method of measuring receive sensitivity was developed. Characterizing the PolySat communications system helped the team gain insight to the unreliable problem.

3.3.1 Preview of Results – Receiver Sensitivity Testing

After the test setup was developed, two revisions of the CP Bus communication system were tested for receive sensitivity. CDH Rev 4 had a sensitivity of around -90 dBm. CDH Rev 5, which includes an LNA, has a sensitivity of approximately -100 dBm. Comparing this to the link budget, a more sensitive transceiver is needed. The ground station receiver, the Yaesu FT-847, had a measured sensitivity of -115 dBm, which is 15-25 dB more sensitive than the PolySat COMM system. The PolySat COMM system should have a sensitivity comparable to the sensitivity of the ground station to help increase reliability of the uplink.

COMM	Sensitivity	Comments

CDH Rev 4	-90 dBm	CP3, CP4
CDH Rev 5	-100 dBm	Includes LNA, CP6
Yaesu FT-847	-115 dBm	Ground Station

Table 3 - Measured sensitivities of two revisions of the PolySat COMM system and the ground station receiver

3.3.2 Additional Testing Performed and Problems Discovered

After characterizing the receive sensitivity of the CP Bus, additional testing was performed as an effort to find any flaws in the COMM system design that would cause a reduction in sensitivity.

A. DC-DC converters, used for efficiency, were previously believed to be causing desensitization of the COMM system. The I^2C data bus, used for data transfer, switches at 100kHz. This is suspiciously close to the 150 kHz IF frequency of the CC1000. Testing was performed for both theories, but it was determined that they are not causing a reduction in sensitivity.

B. Using the setup, noise on the receive line of the CP Bus was monitored, and it was immediately obvious that poor layout resulted in a huge increase of broadband noise. A new layout, using proper PCB layout techniques, could greatly decrease this noise and increase the receive sensitivity.

C. The current testing procedures for qualifying a CDH board as fully functional are not sufficient. During testing, it was found that a “fully functional” board had a serious electrical failure. The U.FL connector (which connects the antenna to the COMM system) has a tendency to fail, resulting in an open circuit. The current testing procedures

should be updated to include measuring the sensitivity of each CDH board and to eliminate the possibility of manufacturing defects of the COMM system. Measuring the sensitivity of a completed satellite can verify system performance before launch.

D. A long duration COMM test showed that the uplink is only approximately 70% successful, even with favorable links conditions. Software testing should be done to determine the cause of this.

E. The test setup outlined in this paper should be used as part of developmental testing of the new bus and final system check-out. It is critical to identify sensitivity problems during development rather than after the satellite is completed and launched. By using this setup, potential problems affecting COMM sensitivity can be identified and resolved early in development.

3.3.3 Documentation of the Sensitivity Measurement Setup Design and Testing Performed

The remainder of this thesis builds upon on the aforementioned preview of conclusions. A detailed discussion of the test setup is included. The testing performed is described along with a discussion of the results. A procedure of using the test setup to measure sensitivity is included in the appendix.

Chapter 4. Measuring Receive Sensitivity

4.1 Overview

In order to measure the receive sensitivity of the PolySat COMM system, a test setup must be developed which allows the accurate adjustment and measurement of the signal reaching the receiver under test. The main goal of this project was to develop a method of accurately measuring the receive sensitivity of the PolySat COMM system. Since it is typical to find receiver sensitivities ranging from -110 dBm to -130 dBm, the setup must be capable of measuring signals of comparably small magnitudes. Stray leakage from the ground station transmitter is easily picked up by the receiver under test, making it very difficult to reduce the received signal strength below the sensitivity threshold of the receiver. A high degree of isolation is required to prevent this from occurring. Reducing a signal to such diminutive amplitudes in a controlled manner is not a trivial task. It is also very difficult to measure such small signals.

4.1.1 Definition of Receive Sensitivity

Receive sensitivity is defined as the minimum input signal that produces a desired output. A receiver's ability to successfully receive and decode a signal requires a minimum Signal to Noise Ratio (SNR). The receive sensitivity is measured in dBm, specified at a particular data rate. Higher data rates of a given receiver result in reduced sensitivity. For the testing performed in this thesis, the receive sensitivity is defined as the weakest signal command (dBm) the PolySat COMM system can decode and respond to. During testing, the signal strength was incrementally reduced until the COMM could no longer decode the signal. After this threshold was determined, the strength of the last successfully decoded command is considered the receive sensitivity. For

the senstivity measurements of this thesis, the receive senstivity is defined as the weakest signal command (dBm) of which the PolySat COMM system could respond to.

4.2 Test Setup Components

The receive sensitivity test setup consists of six main components: an RF source, an attenuation stage (with variable attenuator), a resistive splitter, a Low Noise Amplifier (LNA), a spectrum analyzer, and a custom built Faraday Cage. An overview of the system is shown in Figure 12.

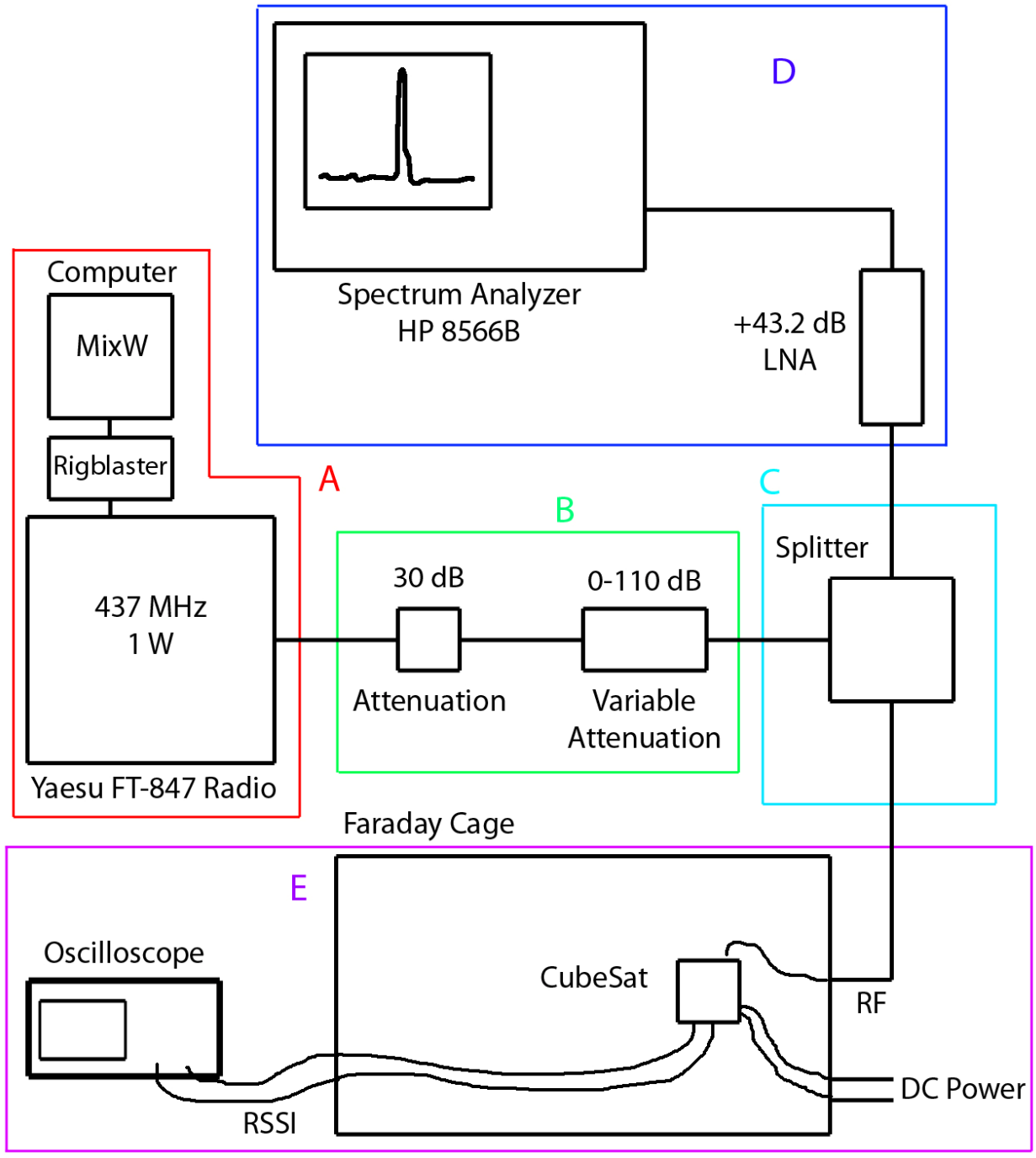


Figure 12 - System level overview of the setup developed used to measure the receive sensitivity of the PolySat COMM system.

The Yaesu radio, connected to a computer via a RigBlaster, sends a command to the satellite (Section A of Figure 12). Commands are manually entered in the MixW software inferface. The MixW software serves as the Terminal Node Controller (TNC) and interfaces to

the Yaesu FT-847 transciever. With a power output of 1W, the RF signal is reduced to 0 dBm as it travels through the 30 dB attenuator. The variable attenuator can further reduce the signal by up to 110 dB (shown in Section B of Figure 12). A resistive power splitter equally divides the signal into two paths (Section C of Figure 12). Half of the signal goes to the HP8566A Spectrum Analyzer for measurement, where a Low Noise Amplifier (LNA) is used to increase the sensitivity of Spectrum Analyzer (Section D of Figure 12). The other half goes to the isolated satellite in the Faraday Cage (Section E of Figure 12). Since the signal is equally split, the Spectrum Analyzer is used to determine the signal reaching the satellite. A power meter was used to verify the accuracy of the Spectrum Analyzer. The accuracy of receive sensitivity measurements obtained with the system shown in Figure 12 is +/- 2 dB. The relative accuracy (comparing two measurements obtained with the test setup) is 2 dB. Using the variable attenuator, the signal magnitude can be reduced until the satellite no longer responds, establishing an approximate threshold of sensitivity.

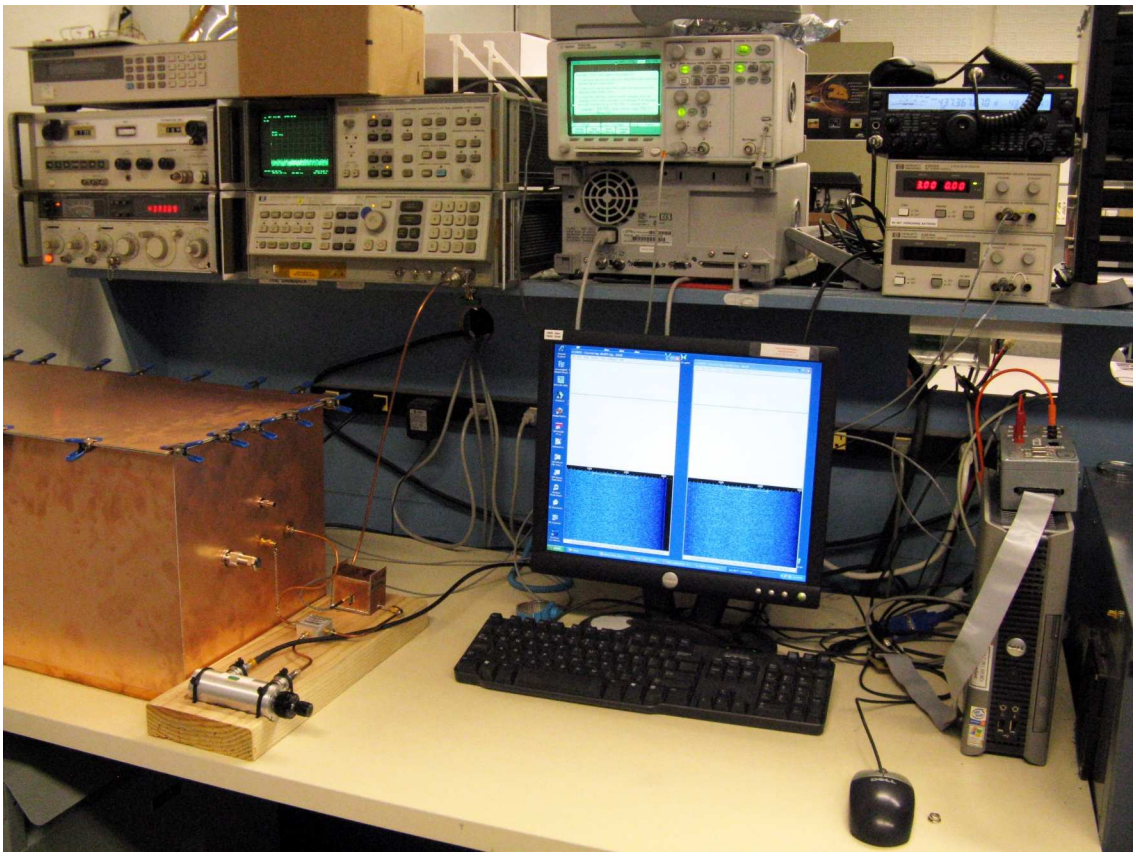


Figure 13 - Sensitivity Measurement setup: this shows all the necessary components required for measuring sensitivity. This setup was used to measure the sensitivity of two revisions of the PolySat COMM system and the ground station receiver.

4.3 RF Source

The first component of the setup is the RF source (Section A of Figure 12). For calibration of the test setup (discussed in Section 4.10), the HP 8640B RF Source was used. By providing a signal of variable magnitude at 437 MHz, a Spectrum Analyzer can be used to quantify the signal amplitude as a function of attenuation applied. For the actual sensitivity measurements (Section 4.11), the Yaesu FT-847 Amateur Transceiver is used with a laptop to send actual commands to the satellite or receiver under test. Commands can be sent from MixW

interfaced to the FT-874 radio (Section A of Figure 12), and responses from the satellite are also monitored with MixW.

4.4 Attenuation Stage

In order to vary the amplitude of the signal reaching the DUT, a variable attenuator is placed directly after the 30 dB attenuator. The JFW Model 50DR-001 variable attenuator can be adjusted from 0-110 dB in 1 dB steps [10].

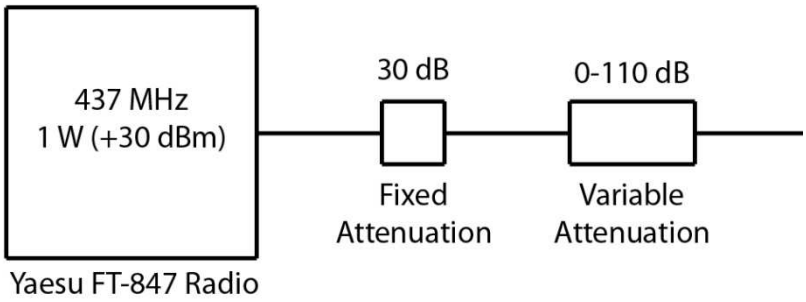


Figure 14 - Attenuation Setup allowing signal strength to be adjusted from 0 to -110 dBm

A table outlining the specifications of the variable attenuator is presented below. Full specifications can be found in the datasheet online.

JFK 50DR-001-N Variable Attenuator	
Frequency Range	DC-1000 MHz
Attenuation Range	0 - 110 dB
VSWR	1.2:1 max (DC-500 MHz)
Insertion Loss	0.5 dB max
Attenuation Accuracy	+/- 0.2 dB or 1%
RF Input Power (AVG)	2 W

Table 4 - Variable Attenuator Characteristics

During sensitivity testing, a high power dissipation 30 dB attenuator is added to the 433 MHz output of the Yaesu FT-847 transceiver to reduce the power from 1W to 1mW. This is required since even the minimum output power on the 433 MHz band is approximately 1W. With the

power effectively reduced, a variable attenuator is added to further reduce the signal by 0-110 dB. This provides the necessary range for determining the minimum detectable signal.

4.5 Resistive Power Splitter

In order to accurately measure the signal reaching the DUT (Section E of Figure 12), the path must be split into two separate but equal paths (Section C of Figure 12).

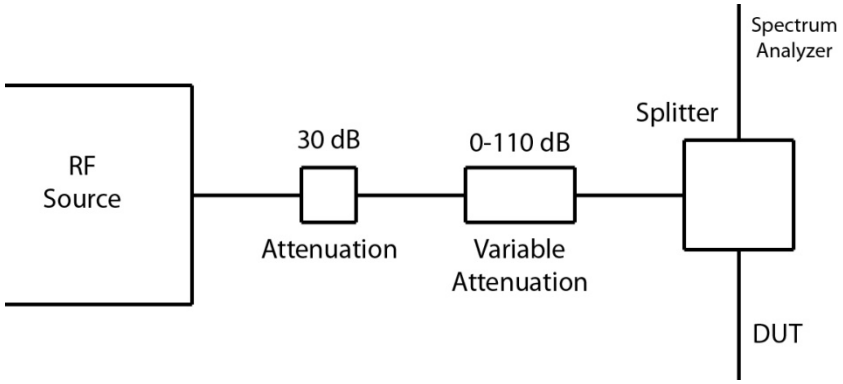


Figure 15 - The resistive power splitter divides the signal equally to both the DUT and Spectrum Analyzer

To do this, a resistive power splitter was used. Both ports are 6 dB down from the input port. Half the power (3 dB) is dissipated in the resistive network, and the remaining power is split equally (another 3 dB) between the two ports. The ZFRSC-42-S+ Splitter features a wide bandwidth, low insertion loss, and excellent amplitude imbalance characteristics.

Frequency	DC-4200 MHz
Insertion Loss	0.1 dB
Amplitude Imbalance	0.02 dB
Power	0.75 W

Table 5 - Characteristics of ZFRSC-42-S+ Power Splitter

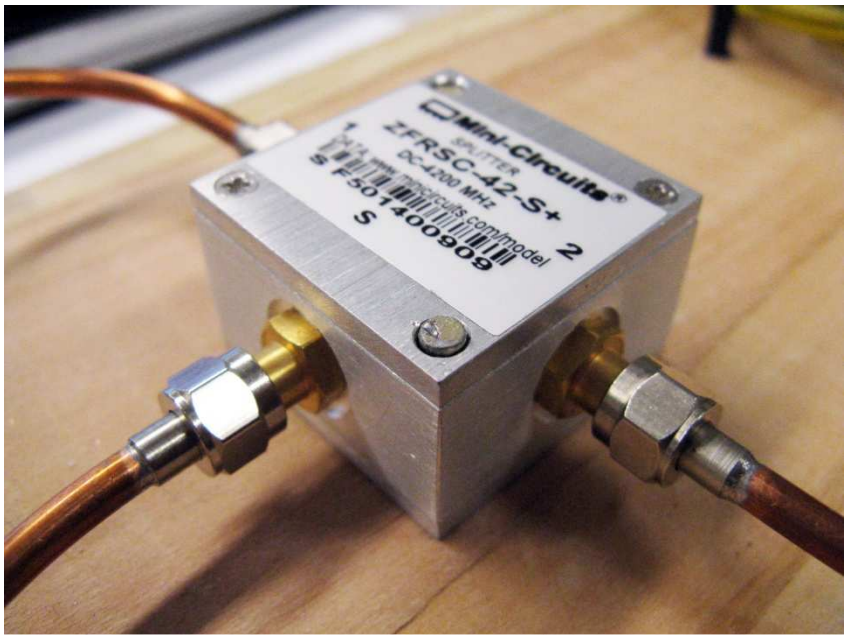


Figure 16 - ZFRSC-42-S+ Power Splitter. Signals 6 dB down from the original signal (at port S) will appear at ports 1 & 2. With signals of equal magnitude reaching the Spectrum Analyzer and the DUT, the signal strength at the DUT is easily measured.

4.6 Low Noise Amplifier

Following the attenuation path (Section B of Figure 12), a resistive splitter divides the signal into two paths (Section C of Figure 12). The first path, used to measure signal strength, feeds directly to a Low Noise Amplifier (LNA) attached directly to the Spectrum Analyzer (Section D of Figure 12). By using a gain block, the Spectrum Analyzer's sensitivity is significantly increased.

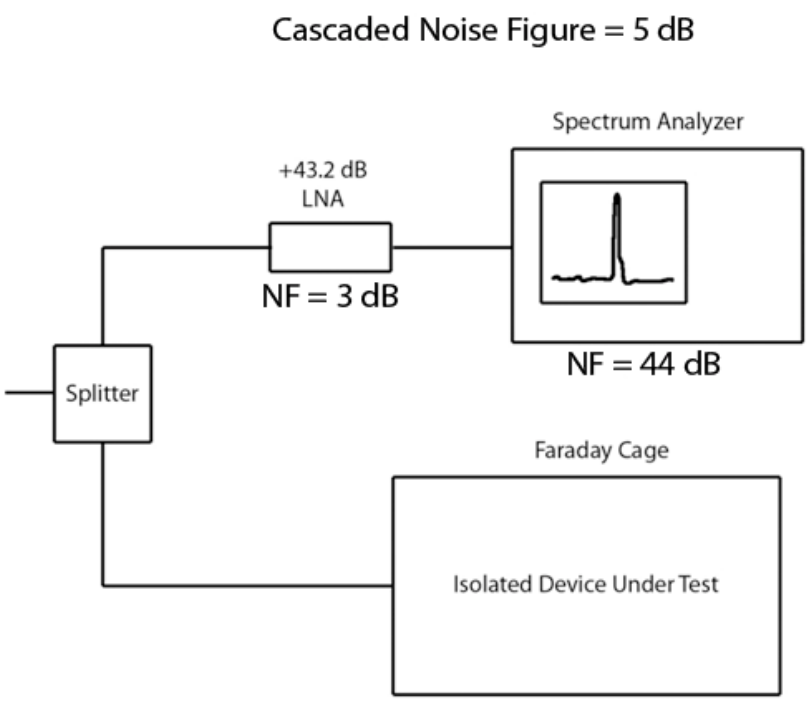


Figure 17 - Low Noise Amplifier used to increase sensitivity of the Spectrum Analyzer. The resistive splitter divides the RF path, and the Spectrum Analyzer is used to measure the amplitude of the signal reaching the satellite in the Faraday Cage.

The other path, used during sensitivity measurement, goes directly to the Faraday Cage (Section E of Figure 12). It is important to note that the signal reaching the Faraday Cage is the same amplitude of the signal reaching the Spectrum Analyzer (after subtracting off the LNA gain). This allows the user to accurately measure the RF signal going into the Faraday Cage. Although the test setup does not change, it is important to measure the signal strength during every test since variations in the output power of the Yaesu FT-847 can occur.

4.6.1 Design of Low Noise Amplifier

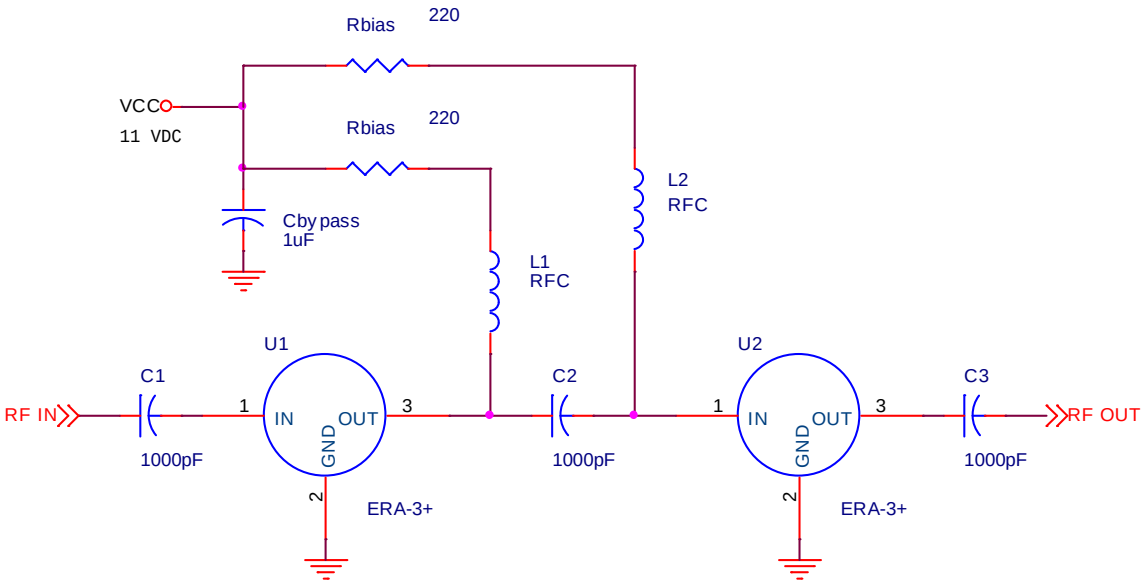


Figure 18 - Schematic of the custom built LNA

Using two drop-in monolithic amplifiers and biasing components, a two-stage LNA was built. Monolithic amplifiers are gain blocks with input and output internally matched to 50Ω. Providing a gain of 42.3 dB, it increases the sensitivity of the Spectrum Analyzer tremendously. In Figure 18, capacitors C_1-C_3 provide a DC block, while C_{BYPASS} filters any noise of the power supply. The R_{BIAS} resistors provide the required current, and RF Chokes were added to prevent AC loading on the output. Using Mini-Circuits' application circuit, two gain blocks were cascaded to obtain a gain of 42.3 dB.

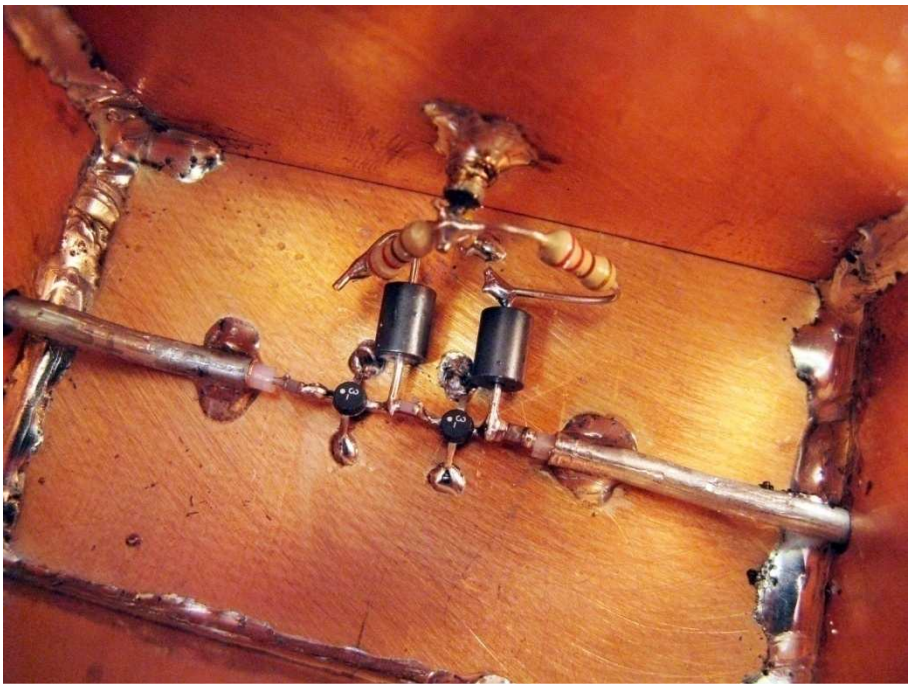


Figure 19 - Construction of LNA.

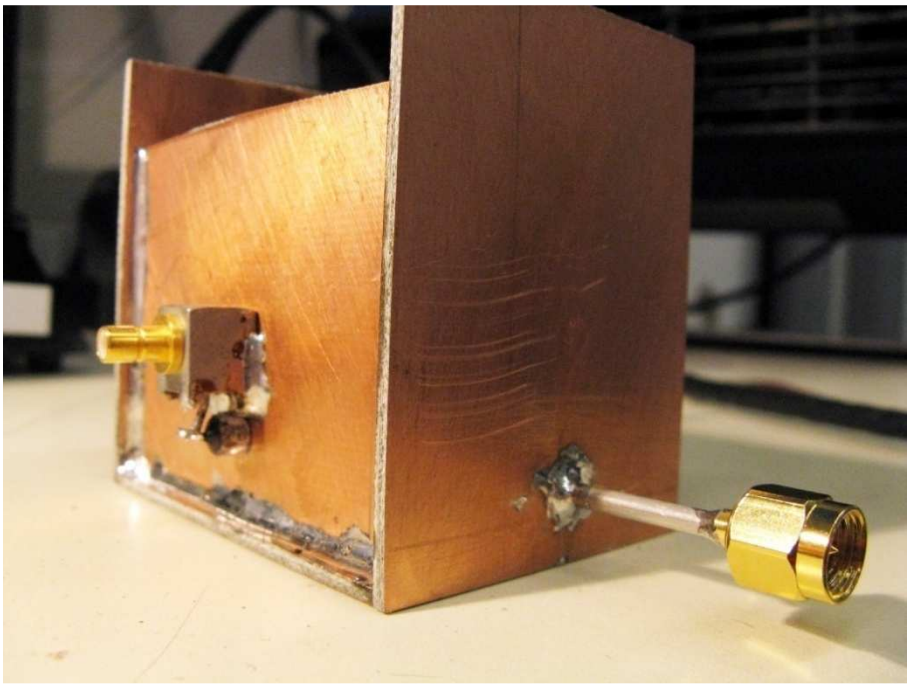


Figure 20 - Miniature Faraday Cage surrounding LNA

To prevent amplification of unwanted noise or signals, the LNA was completely enclosed with unetched FR4 PCB. This is important since the actual signals are of such small magnitude, ranging from -50 dBm to -110 dBm, that any RF leakage from the RF source or radio could be

inadvertently amplified. In order to supply the proper DC biasing, a feed-through capacitor was installed. The feed-through capacitor passes DC signals but shorts AC signals to ground. An SMB connector allows easy connection to a power supply. SMA connectors with semi-rigid coax provide connections at the input and output.

LNA Specifications	
Voltage	11V
Current	72 mA
Gain @ 437 MHz	+42.3 dB
Max Input Power	-5 dBm

Table 6 - LNA Specifications: required voltage bias, typical operating current, and absolute maximum power

The LNA is a small signal amplifier, meaning that it is not designed to amplify larger signals (0 dBm or 1 mW). The maximum input power (shown in Table 6) is -5 dBm or 0.316 mW, and it is important to not to exceed this rating otherwise permanent damage to the LNA would occur.

4.6.2 Input Return Loss of LNA

Return loss is a measure of the reflected power at a port, compared to the power incident upon that power. Typically denoted in magnitude form, it describes how well matched the LNA is to the 50Ω system.

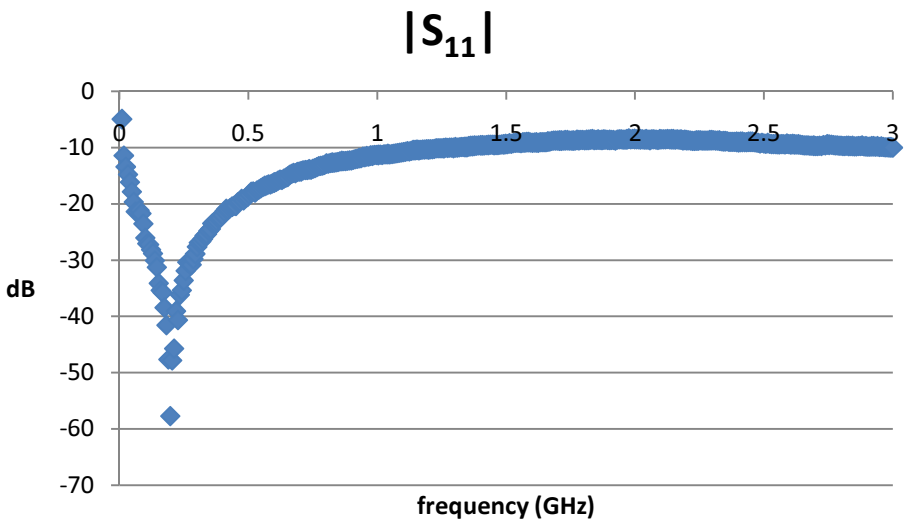


Figure 21 - S_{11} of LNA

S_{11}	
f (GHz)	**dB**
0.4286	-20.778
0.436075	-20.559
0.44355	-20.356
0.451025	-20.395

Table 7 - S_{11} across the 70 CM Amateur Radio band

The input return loss is greater than 20 dB across the 430-450 MHz amateur radio band. Below 0.5 GHz, the input is well matched to a 50Ω system. As the frequency increases past 1 GHz, the return loss decreases to approximately 10 dB.

4.6.3 Output Return Loss of LNA

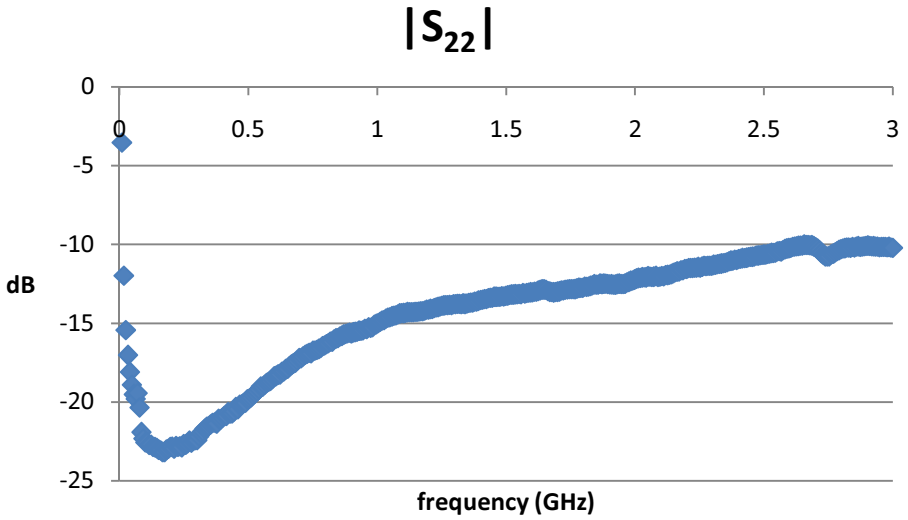


Figure 22 – S_{22} of LNA

S_{22}	
f (GHz)	dB
0.4286	-20.746
0.436075	-20.73
0.44355	-20.608
0.451025	-20.341

Table 8 - S_{22} of LNA

The output of the LNA has a return loss of greater than 20 dB across the 430 – 450 MHz amateur band. It slowly approaches 10 dB around 2.5 GHz.

4.6.4 Forward Gain of LNA

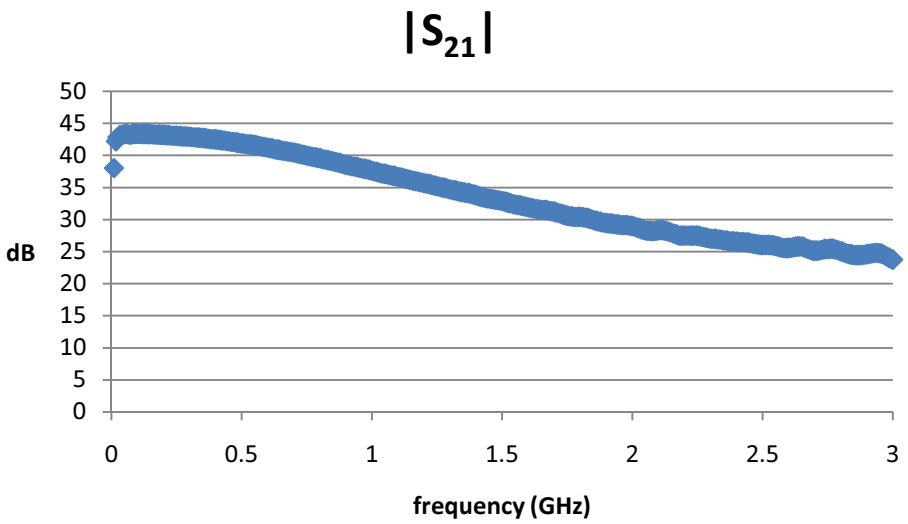


Figure 23 - Forward Gain S_{21} of LNA

S_{21}	
f (GHz)	dB
0.4286	42.292
0.436075	42.296
0.44355	42.207
0.451025	42.195

Table 9 – S_{21} across the 70 CM Amateur Radio band

To improve the sensitivity of the Spectrum Analyzer, a large gain is required. From the datasheet, each MMIC block has a typical gain of 22.1 dB (at 0.1 GHz) and 21 dB (at 1 GHz). With two gain blocks in series, the expected gain is approximately 42 dB (below 1 GHz). As the frequency increases to 2 and 3 GHz, the typical gain of each block decreases to 18.7 dB and 16.4 dB (respectively). The expected total gain is approximately 36 dB (at 2 GHz) and 32 dB (at 3 GHz). Using the Vector Network Analyzer (VNA), the forward gain of the LNA was measured to be greater than 42 dB across the 430-450 MHz amateur band. Even as the gain drops off significantly to approximately 30 dB at 2 GHz and less than 25 dB at 3 GHz, this gain is still great enough to greatly increase the Spectrum Analyzer's sensitivity. If the setup is used at a

higher frequency, the change in forward gain must be noted. This is because the gain is subtracted off to determine the actual signal going to the Faraday Cage during system calibration.

4.6.5 Reverse Gain of LNA

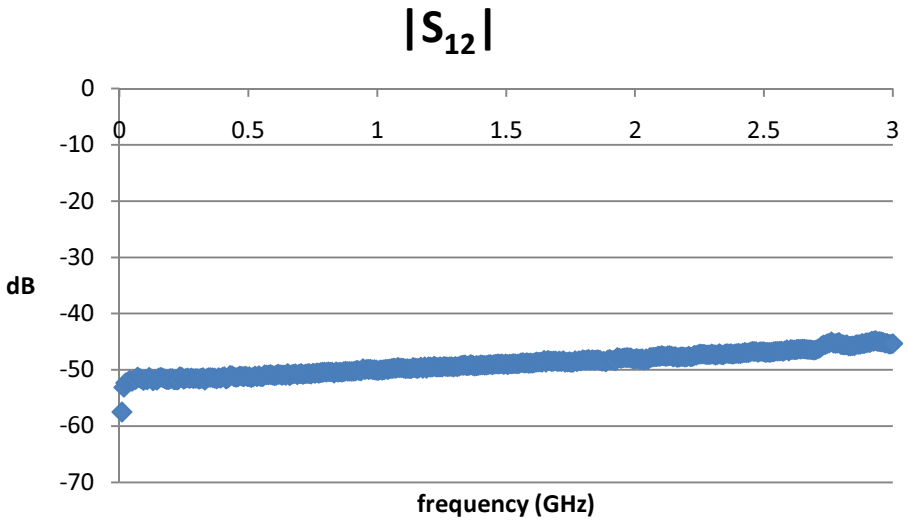


Figure 24 - Reverse Gain S_{12} of LNA

S_{12}	
f (GHz)	dB
0.4286	-51.056
0.436075	-51.034
0.44355	-51.236
0.451025	-51.368

Table 10 – S_{12} across the 70 CM Amateur Radio band

The Reverse Gain S_{12} is less than -50 dB across the 430-450 MHz amateur band, indicating a high degree of reverse isolation.

4.6.5 1 dB Compression Point

As the input signal to an amplifier is linearly increased, at some point the output no longer increases linearly. If the input signal continues to increase, the amplifier saturates, or can no longer amplify the signal. The 1 dB compression point indicates the power level which causes the amplifier gain to decrease by 1 dB [1]. This can be referred to either the input or output.

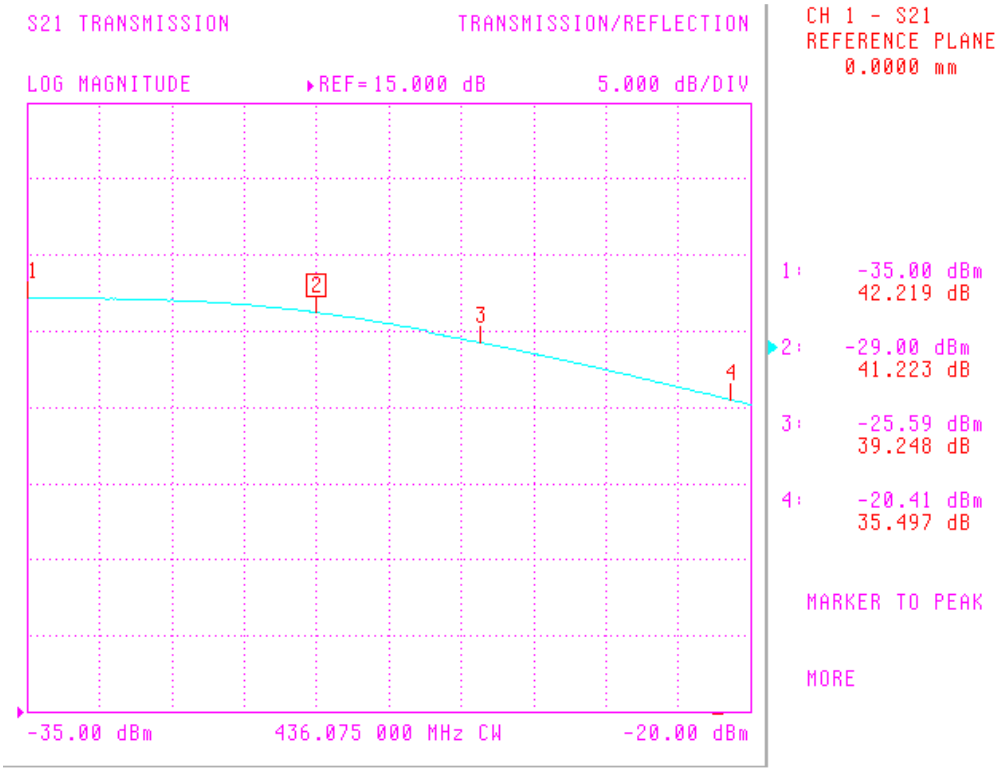


Table 11 - 1 dB compression point of LNA (output)

The 1dB compression point, referenced to the output, occurs when the input signal amplitude reaches -29 dBm. The gain drops from 42.2 dB to 41.2 dB. In order to prevent errors during characterization or testing, the magnitude of the signal reaching the LNA should be several dB less than -29 dBm. In order to prevent permanent damage, the maximum signal at the input should be significantly less than 330 mW (+24.2 dBm).

4.6.6 Noise Figure of LNA

Noise Figure is a measurement of the degradation of Signal-to-Noise Ratio (SNR). For a cascaded system, the Noise Figure can be calculated using the following equation.

$$F = F_1 + \frac{F_2 - 1}{G_1}$$

Equation 2 - Noise Figure

Using typical ERA 3+ datasheet values at f = 1 GHz, $G_1 = G_2 = 21$ db (125.89). Also, $F_1 = F_2 = 2.6$ dB, or 1.8197.

$$F = 1.8197 + \frac{1.8197 - 1}{125.89} = 1.8262 = 2.62 \text{ dB}$$

Equation 3 - Calculated Noise Figure of the Low Noise Amplifier

Equation 3 shows the calculated Noise Figure for the LNA at f = 1 GHz. Since the datasheet value doesn't change much over the 0.01 – 1GHz range, similar performance can be expected at 437 MHz. The Noise Figure of the LNA was measuring using the setup shown in Figure 25.

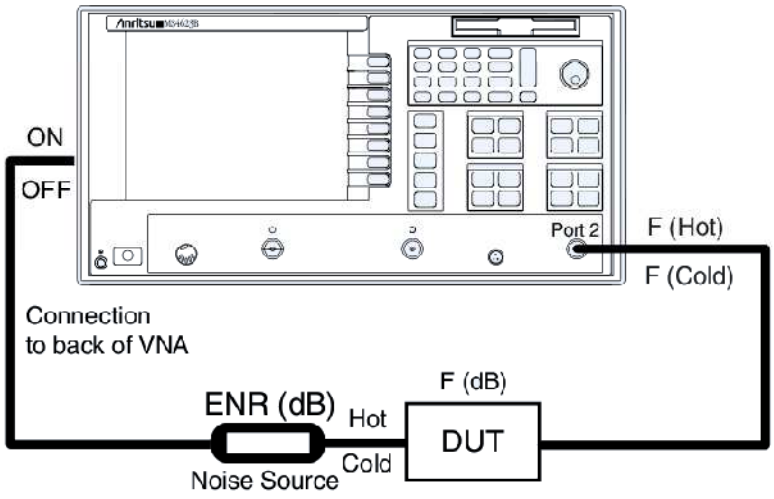


Figure 25 - The test setup used to measure the Noise Figure of the Low Noise Amplifier [22]

The measured noise figure (Table 12) remains close to the datasheets typical values up through 1 GHz, but increases by almost 2 dB at 2 GHz. At 3 GHz, the noise figure was measured at 7.298 dB. However, the measured noise figure remains at approximately 3 dB throughout the 430-450 MHz amateur radio band, which is very close to the typical values listed in the ERA 3+ datasheet [20].

	f (GHz)	Noise Figure (dB)
Typical Values (datasheet)	0.01	2.7
	1	2.6
	2	2.8
	3	2.9
Measured Values	0.05	3.127
	1	3.302
	2	5.233
	3	7.298

Table 12 - Typical and measured Noise Figures from 0.010-3 GHz

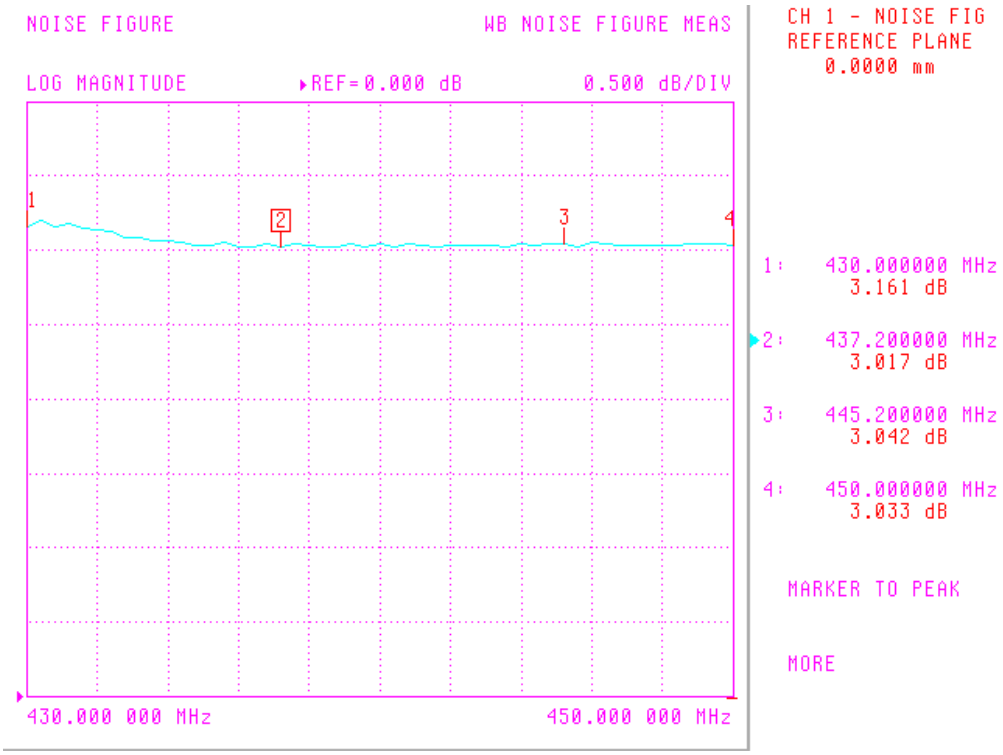


Figure 26 - Measured noise figure over the 430-450 MHz range

4.7 HP8566A Spectrum Analyzer

System calibration consists of characterizing the signal reaching the DUT. To do this, a splitter divides the signal and directs it to the DUT and a Spectrum Analyzer. The LNA, attached to the front of the Spectrum Analyzer, increases sensitivity. With a Resolution Bandwidth (RBW) of 3 kHz, the Displayed Average Noise Level (DANL) is approximately -95 dBm/3kHz or -129.77 dBm/Hz. The noise figure of the Spectrum Analyzer is the difference of the noise floor (dBm/Hz) and the thermal noise power (-174 dBm/Hz).

$$NF_{Spectrum\ Analyzer} = -129.77\ \text{dBm/Hz} - (-174\ \text{dBm/Hz}) = 44.23\ \text{dB}$$

Equation 4 - Calculated Noise Figure of the Spectrum Analyzer

It is important to note that the above noise figure was determined with the attenuation set to 10 dB on the Spectrum Analyzer. Without the 10 dB attenuation, the noise figure would be 34.23 dB. The noise figure of the Spectrum Analyzer can be significantly reduced by placing a large gain block on the front end (shown in Section D of Figure 12 and in Figure 27).

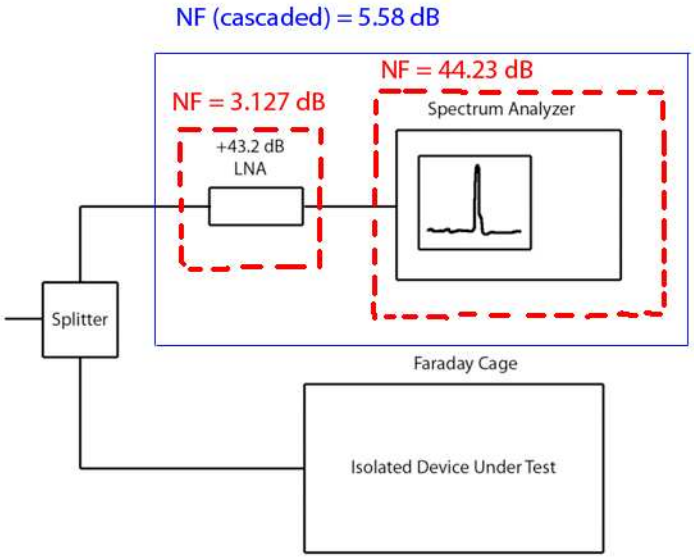


Figure 27 - The Noise Figure of the cascaded system (LNA and the Spectrum Analyzer) approaches the Noise Figure of the first stage of the cascaded system (LNA). This increases the sensitivity of the Spectrum Analyzer.

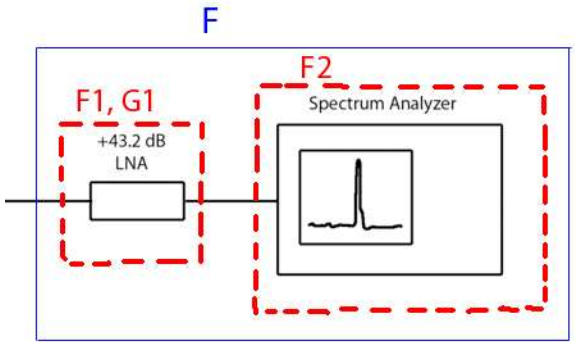


Figure 28 - Noise Figure F of the two stage cascaded system (LNA and Spectrum Analyzer).

The theoretical Noise Figure of the cascaded system (Figure 28) is calculated using Table 13 and Equation 5.

	dB	Linear
F_1	3.127 dB	2.0545
F_2	44.23 dB	26,485
G_1	42.3 dB	16,982

Table 13 - Noise Figure and Gain of individual stages in dB and linear equivalents, used to calculate the Noise Figure of cascaded Spectrum Analyzer and LNA.

$$F = F_1 + \frac{F_2 - 1}{G_1} = 2.0031 + \frac{26{,}485 - 1}{16{,}9824} = 3.614 = 5.58 \text{ dB}$$

Equation 5 - Noise Figure of the Spectrum Analyzer and the LNA cascaded together

The Noise Figure of the cascaded LNA and Spectrum Analyzer (Section D of Figure 12) shown in Figure 28 becomes slightly higher than the noise figure of the first stage. By adding the LNA to the front end of the Spectrum Analyzer (Section D of Figure 12), the sensitivity of the Spectrum Analyzer is greatly increased.

4.8 Faraday Cage

The Faraday Cage (Section E of Figure 12) isolates the satellite, or receiver under test, from stray RF radiation of the Yaesu FT-847. Previous attempts at measuring the receive sensitivity failed due to a lack of isolation (from stray RF or radio leakage) [3] [4]. Without sufficient isolation, the satellite will respond regardless of how much attenuation is added to the setup. The CC1000 transceiver has a typical receive sensitivity of -110 dBm (2400 baud FSK modulated data), which is 0.01 pW of power! This illustrates that even very weak RF radiation can seriously pose a problem for sensitivity testing. RF leakage from the Yaesu FT-847 is easy to observe by attaching a 50 Ohm load to the 433 MHz output. Ideally, all the output power would

be dissipated into the 50 Ohm load, but a satellite placed across the room will easily respond to commands sent. This simple test shows that a very high degree of isolation is required.

4.8.1 Screen Rooms

In order to properly characterize the Received Sensitivity (RSSI) of the satellite, a high level of isolation is required to prevent stray radiation from being picked up by the sensitive receiver. Cal Poly has three screen rooms on campus, all operated by the Electrical Engineering (EE) department. Two are located in the EE department (Building 20). One is in the RF Lab, room 116, and the other is located in the Communications Lab, room 118. The third screen room is located in Professor Dean Arakaki's laboratory near the RFID lab in Building 4. Before the rooms could be utilized, each had to be characterized by determining the approximate attenuation at the frequency of interest (437 MHz). The original plan was to use one of the existing rooms for sensitivity testing, but the isolation of each room proved to be insufficient.

Figure 29 - The screen room in RM 116

It was thought screen room in room 116 would be ideal to use because it is conveniently located in the RF lab, which contains important test equipment such as spectrum analyzers and network analyzers. Additionally, an N-Type bulkhead connector could be installed, which would allow RF signals to be passed into the cage. However, the attenuation at 437 MHz was not enough to prevent stray radiation from triggering the satellite. This was discovered by placing the satellite in the screen room and sending commands from outside with the Yaesu radio. Even with the minimum RF power and the output of the FT-847 terminated with a 50Ω load , the satellite consistently responded. This indicated that some sort of RF leak was present, most likely due to the ceiling vents or light switch. Or, the screen room wasn't designed for attenuation at UHF (Ultra High Frequencies).

Figure 30 - Screen room in RM 118 (left) and accompanying RF passthrough (right)

The screen room in RM 118 offers comparable attenuation to the cage in room 116. The RF passthrough is a PL-258 bulkhead. This connector, although labeled UHF, isn't suitable for frequencies over 300 MHz, and wasn't designed for the typical 50Ω characteristic impedance of

most connectors and cables used in today's RF applications (it does not have a constant 50Ω impedance). Although the insufficient attenuation was the limiting factor, the RF passthrough was a good indicator that the room would not offer enough attenuation at UHF.

The third screen room on campus, located in Professor Dean Arakaki's lab near the RFID lab in Building 4, is the EMC Chamber designed and operated by Professor Dean Arakaki. In addition to RF isolation, ferrous ceramic tiles line the interior of the room, allowing for conducted and radiated emissions testing.

Figure 31 - EMC Chamber at the RFID lab in Building 4

Testing the EMC Chamber at 437 MHz showed attenuation at 437 MHz slightly higher as compared to the other screen rooms, but not high enough to warrant use. Some of the modifications done to the chamber may have compromised the attenuation at UHF. Furthermore, the room is inconveniently located in Building 4, a substantial walk from the PolySat lab in the MSTL. Although this sounds trivial, it would require the use of a vehicle to bring all the test equipment (radio, power supplies, test setup, etc) which would be very inconvenient. It would also require an RF pass-through installed. Although each room is a valuable asset to the EE Department, none of them offered enough attenuation at 437 MHz. A HP8566A Spectrum

Analyzer with antenna attached was placed inside the screen room, and a handheld radio was placed outside transmitting at 437 MHz. The difference in measured power with the screen room doors open and closed provide an approximate measure of isolation. A block diagram of the setup is shown in .

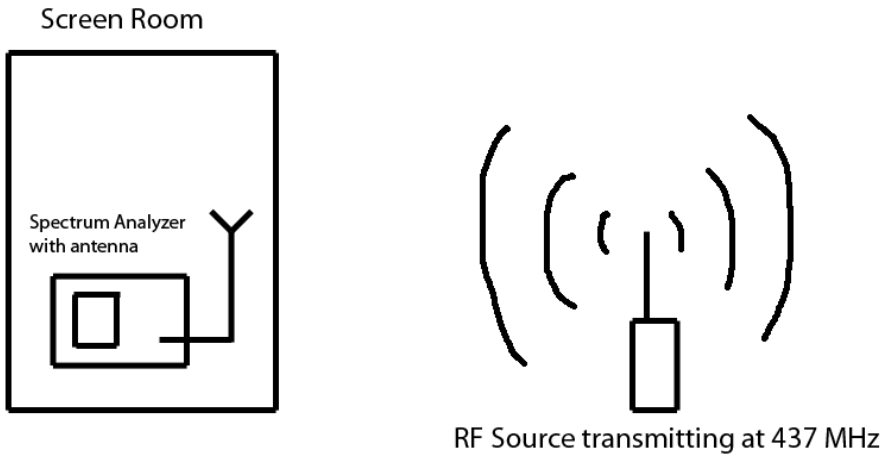


Figure 32 - Testing each screen room for isolation: a handheld radio transmitting at 437 MHz was placed outside each screen room, and the HP8566A Spectrum Analyzer with antenna was used to measure the power with the screen room door open and closed. The difference in measured power with the screen room door open and closed provided an approximate level of attenuation.

Screen Room	Approximate Isolation (dB)
Room 116, Building 20	60
Room 118, Building 20	50
EMC Chamber (Arakaki's Lab)	60

Table 14 - Comparison of the attenuation of each Screen Room. Each room does not provide enough isolation at UHF.

The only alternative was to build a custom Faraday Cage. After building the cage, a huge advantage was noted: sensitivity testing requires a lot of resources from the PolySat lab. Sensitivity testing is most efficiently conducted inside the PolySat lab. In other words, it would have been very inconvenient to conduct testing outside of the PolySat lab.

4.8.2 Custom Faraday Cage

According to Gauss' Law, an electric field will not penetrate a perfectly conducting enclosure. Instead, the current will reside at the top of the conductor, depending on the frequency. The higher the frequency, the more concentrated the current will be at the surface of the conductor. This is known as the skin effect. The skin depth, dependent on frequency, can be calculated using the equation below.

$$\delta = \frac{1}{\sqrt{\pi \mu_0}} \sqrt{\frac{\rho}{\mu_r f}}$$

Equation 6 - Skin depth formula

δ	skin depth in meters
μ_0	$4\pi \times 10\text{-}7$ H/m
μ_r	relative permeability (0.999994 for copper)
ρ	resistivity of the medium in Ω·m (1.72×10^{-8} for copper)
f	frequency of the wave in Hz

Table 15 - Variables affecting skin depth of material

After simplifying the above equation (and converting from meters to inches), the skin of an RF signal at 437 MHz penetrating copper is calculated in Equation 7.

$$\delta = \left(\frac{\rho}{\pi \, \mu \, f}\right)^{\frac{1}{2}} = \left(\frac{6.787 \times 10^{-7} \Omega \, in}{2\pi \left(3.19 \times 10^{-8} \frac{W}{A \, in}\right) (437 \times 10^{6} Hz)}\right)^{\frac{1}{2}} = 124 \, microns$$

Equation 7 – Calculating the skin depth of copper of a 437 MHz signal

At 437 MHz, the thickness of the Faraday Cage material is not an issue. With such little penetration, the cage can be constructed with conducting material as thin or thick as convenient. In order to isolate the satellite from stray RF radiation, a Faraday Cage can be built based on the

principles described above. In principle, any high conductivity box would work fine. The thickness of the metal is not of great importance, because at the frequency of interest (437 MHz), the skin depth of copper is very small.

4.8.3 Construction

Aluminum, Steel, or any other high conductivity metal could be used, but copper was chosen because the enclosure could be easily soldered rather than welded. Although welding is also practical, it would require specialized equipment and a person skilled in welding. Since copper sheeting is quite expensive, double sided blank FR4 PCB (1 OZ copper) was used. The board provided the structural rigidity, and the unetched copper served as the solid conductor. As previously shown, the skin depth of a signal at 437 MHz is 0.124 mils, whereas 1 OZ copper has an average thickness of 1.4 mils. Due to the small size of the satellite, a small enclosure could be made which provides portability advantages. A concept of the enclosure is shown in Figure 33.

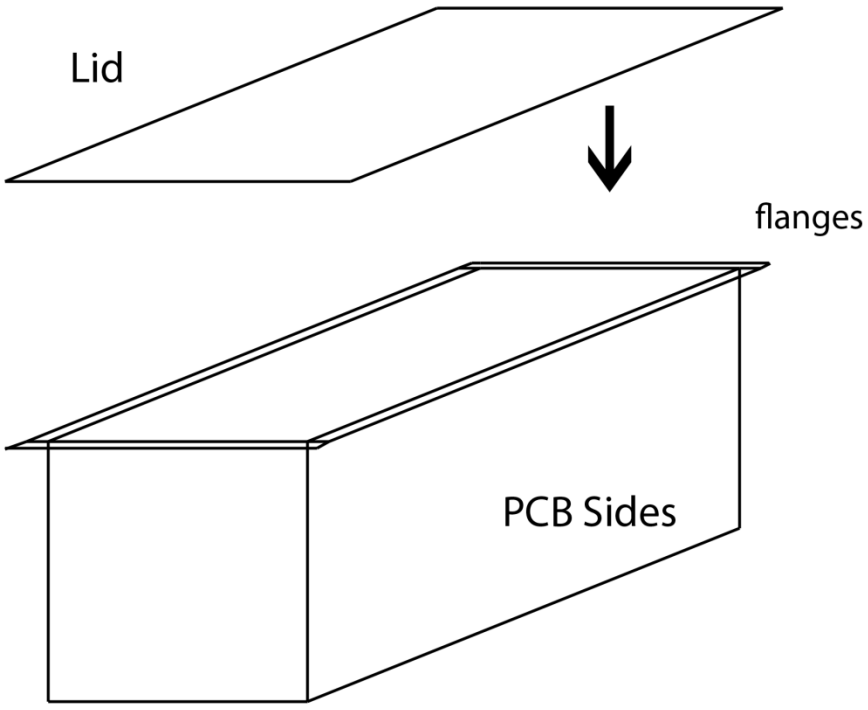


Figure 33 - Concept of Faraday Cage construction

Constructing an RF proof enclosure is relatively easy, but usually the opening is the most difficult part in terms of RF isolation. Any RF penetrating the enclosure will typically find its way in through the opening or lid. For simplicity, it was determined that an effective and sealable opening could be implemented by constructing a rectangular box with no top, and adding small flanges perpendicular to the sides. Then, a lid could be rested on top of the enclosure, and sealed by attaching clamps to hold the lid tightly to the enclosure's flanges. Finally, small clamps could apply pressure, providing a tight seal.

Figure 34 - Unetched PCB being soldered together to form the enclosure

Each seam was soldered completely, and copper tape applied to the top flanges and most of the seams.

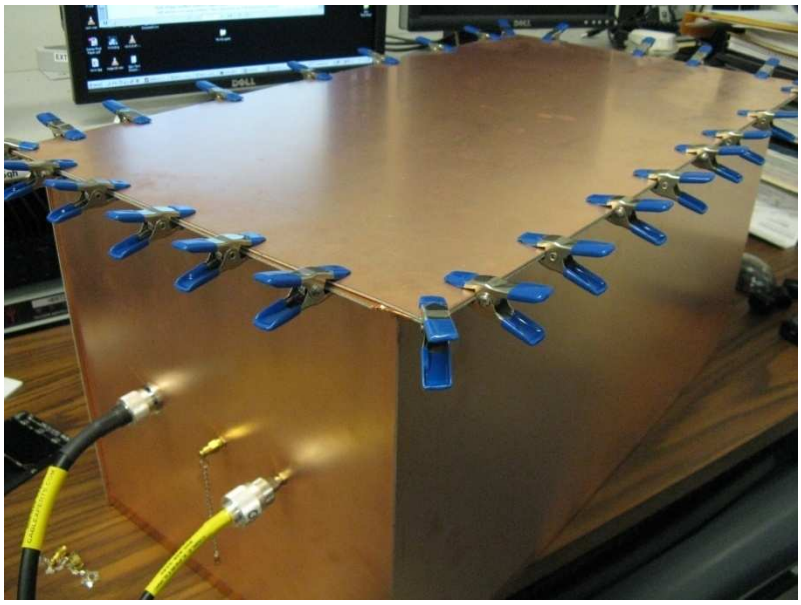


Figure 35 - Completed cage, using clamps to seal the lid. Coax is seen attached to each RF pass-through

Since a larger sheet of PCB has some flex, attaching clamps helps provide a better seal. With the lid totally sealed, the isolation at 437 MHz is easily sufficient to isolate a satellite.

4.8.4 Features

The box was built to be 2’ long by 1’ wide and 1’ tall. This is small enough to allow desktop operation, but still capable of housing an entire P-POD or a 3U satellite with small antennas extended. More importantly, the box can accommodate a satellite with umbilical box, which can provide the 3V and 4.2V voltage rails required to power the CDH.

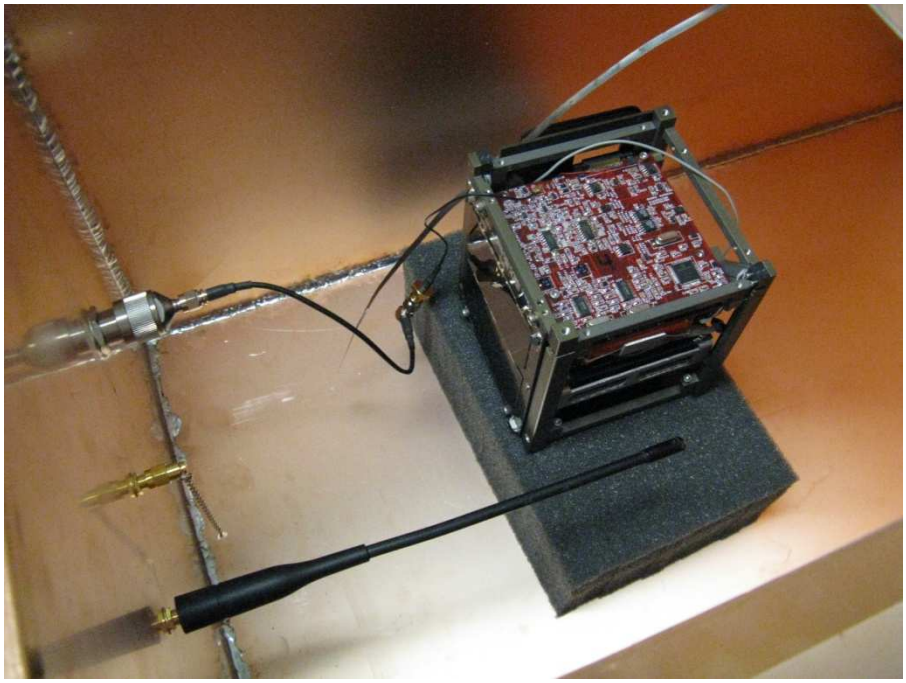


Figure 36 - Spacious interior allows testing on larger satellites (3U) if necessary. CP3 TestSat is attached via the U.FL antenna connector, with CDH Rev 5 (with the LNA amplifier, same CDH flown on CP6).

To pass signals in and out of the enclosure, 4 SMA bulkheads and 1 N Type bulkhead were mounted. 50Ω terminations can be attached to the bulkheads not being used, to ensure radiation does not leak through the SMA and N-Type bulkheads.

Figure 37 - N-Type and SMA pass-through ports. When not in use, each port should be terminated with a 50Ω termination to prevent the possibility of leakage.

Although the N-Type and SMA connectors can pass DC if necessary, dedicated DC pass-through ports were also installed. Since any modifications to the box could compromise the isolation, feedthrough capacitors were used. Feedthrough capacitors shunt any AC signal to ground, while passing DC signals. Two separate pass-through ports were necessary, since the current CP Bus utilizes two voltage levels (3.0V and 4.2V).

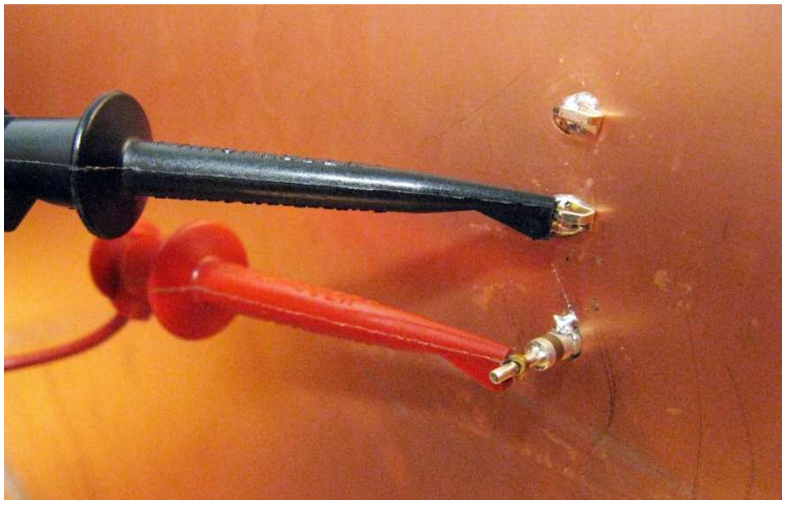


Table 16 - Feedthrough capacitors capable of passing DC power. Ground clips soldered to cage.

To minimize the chance of RF leakage, SMB connectors were connected to the feedthrough capacitors. This allows the use of shielded coaxial cables to connect from the power supply to the Faraday Cage. Compared to standard leads, shielded coax is less likely to act as an antenna and carry signals to the Faraday Cage.

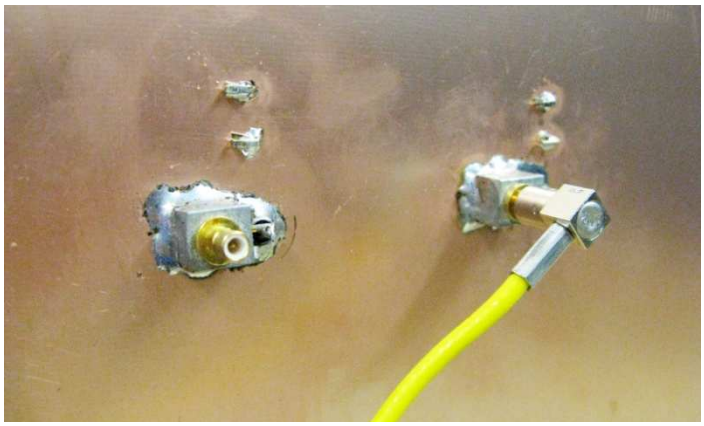


Figure 38 - SMB Connectors used to pass DC power into the Faraday Cage

4.8.5 Attenuation Performance of Faraday Cage

After completing the construction of the Faraday cage, a test was performed to evaluate the enclosure's attenuation at 437 MHz. The first test consisted of placing a source transmitting at 437 MHz inside the cage. Using a spectrum analyzer with an antenna attached, the power of the source was measured while the cage was open and closed. By observing the difference of the two measured powers, an approximate measure of attenuation was obtained. This test is shown in Figure 39.

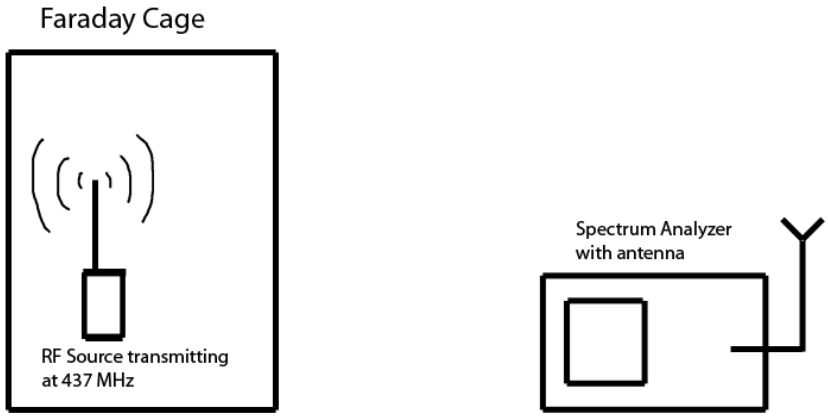


Figure 39 - Testing the Faraday Cage for isolation. A handheld radio was placed inside the cage, transmitting at 437 MHz. The HP8566A Spectrum Analyzer equipped with an antenna was used to measure the signal

strength with the cage closed and open. The difference between these two measurements provides an approximate level of isolation.

It is important to note that this is an approximate attenuation because this does not take into account other factors such as multipath or fading due to reflections.

Isolation Device	Attenuation
Screen Room, Room 116	60
Screen Room, Room 118	50
EMC Chamber	60
Custom Built Faraday Cage	70

Table 17 - Comparison of attenuation of each screen room to the custom built Faraday Cage. The cage offers 10 dB more isolation, which was enough to isolate the satellite from stray radiation.

The Faraday Cage effectively attenuates signals at 437 MHz by at approximately 70 dB. At first, it was thought that the Faraday Cage must attenuate signals by at least 153 dB, which is the worst case path loss for a typical CubeSat orbit. However, the Faraday Cage's purpose is not to simulate the orbital path loss. It is merely to prevent stray leakage (from the radio, connectors, coax, etc) from triggering the COMM system. For this purpose, the Faraday Cage performs very well.

4.9 Other Considerations

4.9.1 RF Leakage

All the components of the setup are connected with lengths of semi-rigid coax. Compared to regular braided coax, the chance of RF leakage is smaller. Semi-rigid coax offers 100% shielding, whereas braided coax does not. Previously, 10 dB and 20 dB attenuators were connected back to back to reduce the approximately 30 dBm output of the Yaesu radio to around

0 dBm. However, after characterization some of the data appeared erroneous. After re-characterizing the system (shown in Figure 12), it was found that RF leaks can bypass attenuators placed back to back. This was only observed to be a problem at higher power levels (greater than 10 dBm). A single 30 dB attenuator was used instead.

4.9.2 Yaesu Radio RF Output Power

The output power of the Yaesu FT-847 radio (at minimum RF power setting) was observed to be constant at one of two power levels: 0 dBm or -19.5 dBm. The output wouldn't change throughout testing, but would be at either power level at startup. Because of this, it is very important to measure the output of the radio during each test. This is considered an anomoly of this particular unit and is not yet fully understand.

4.10 Sensitivity Measurement Setup Characterization

In order to determine the amplitude of the signal reaching the DUT, the sensitivity measurement setup (shown in Figure 12) must be characterized. Using the HP 8640B RF source, a signal of amplitude -20 dBm at 437 MHz provided was fed directly to the setup. The Spectrum Analyzer with LNA was monitored as the variable attenuator was varied from 30 dB to 110 dB. The signal reaching the Spectrum Analyzer is the same amplitude of the signal reaching the DUT (after subtracting off the LNA gain). By characterizing the system, the attenuator setting will correspond to a signal of a specific amplitude. The characterization setup is shown in Figure 40.

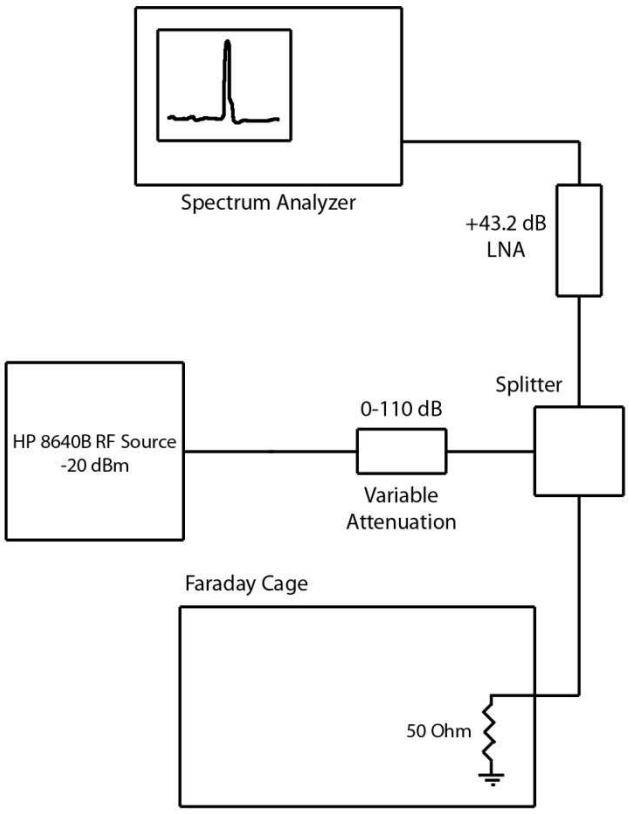


Figure 40 - Characterizing the receive sensitivity setup

For example, if the attenuator is set to 24 dB, the actual signal reaching the DUT is -50.5 dBm. The characterization is done to determine (with a high degree of accuracy) the strength of the signal reaching the DUT. After characterization, a user can easily determine the Minimum Detectable Signal (MDS) of a transceiver by increasing the attenuation until the transceiver no longer responds. Then, the receive sensitivity is simply the signal amplitude corresponding to the attenuation setting at which packets were last received. However, after the output variability of the Yaesu FT-847 was discovered, it is highly recommended to actually measure the signal during each sensitivity test.

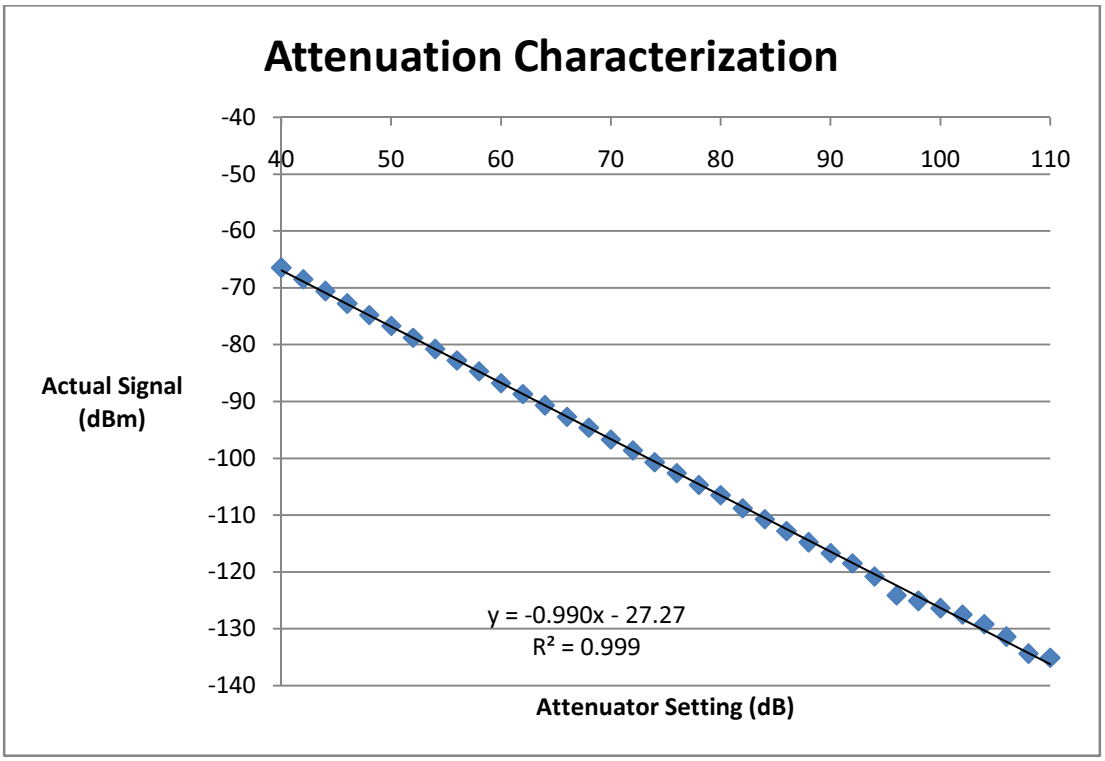


Figure 41 - Actual signal reaching DUT (dBm) versus attenuator setting. The attenuation was adjusted from 40 to 110 dB, and the signal reaching the Faraday Cage (Section E of Figure 12) was measured using the Spectrum Analyzer (Section D of Figure 12). A strong linear response indicates that the test setup (Figure 12) is capable of accurately measuring receive sensitivity.

In Figure 41 there is a strong linear correlation between the actual signal and the attenuator setting. This indicates that the user can expect an accurate adjustment of the signal when adjusting the attenuator. If the attenuator is adjusted by 10 dB, the corresponding signal should be reduced by 10 dB. The linear correlation shows that this does indeed happen. For example, when the attenuator is adjusted from 50 to 60 dB, the measured signal is reduced from amplitude of -76.7 dBm to -86.8 dBm. The percent error, calculated in Equation 8, is only 1%.

$$Percent\ Error = \frac{Measured - Expected}{Expected}\ x\ 100 = \frac{(-76.7 - -86.8) - 10}{10} x\ 100 = 1\%$$

Equation 8 – Equation used to calculate Percent Error

Throughout most of the characterization, the linear relationship remains strong, with a percent error of less than 10%. But with the attenuator set to 94 dB or higher, the linear relationship seems to deteriorate. Percent error varies greatly, in some cases reaching 90%. Although this suggests that the setup isn't accurate for signals with a magnitude of less than -120 dBm, this isn't the case. The accuracy of the measurement signal is limited by the sensitivity of the Spectrum Analyzer. The displayed average noise floor of the Spectrum Analyzer is approximately -94 dBm (RBW set to 30 kHz, default attenuation of 10 dB). A RBW of 30 kHz was chosen because it is the system noise bandwidth of the transceiver utilized in the PolySat COMM system. With measured signals falling below approximately -64 dBm, corresponding to actual signal strength of -106.3, the Signal to Noise Ratio (SNR) becomes less than 10 dB. At measured signals below -77.7 dBM, corresponding to a magnitude of -120 dBm, (attenuator setting of 94 dB) the SNR is very low (approximately 3 dB). The power of the measured signal is only twice that of the noise power, significantly reducing the accuracy of the measurement. Furthermore, the marker used to read the amplitude of the signal starts to fluctuate significantly (varying by as much as 1-2 dB) increasing the error in the measured signal. Although 1 dB does not seem like much variation, the system was characterized in 2 dB increments, so an error of 1-2 dB corresponds to a percent error of 50-100%. The accuracy of the system behaves as expected, even as the signal power becomes less than -120 dBm.

4.11 Test Setup – Measuring Sensitivity of the PolySat COMM System

The sensitivity test setup (shown in Figure 12) was designed to measure the receive sensitivity of the PolySat COMM system. Recalling the back to the definition listed in Section 4.1.1, the receive sensitivity of the PolySat COMM system is the weakest signal command (measured in dBm) in which the COMM system could reply to. The PolySat COMM system

outputs approximately 1W of RF power (+30 dBm) [3]. This means that a response to a command will result in +30 dBm of RF power entering the power splitter.

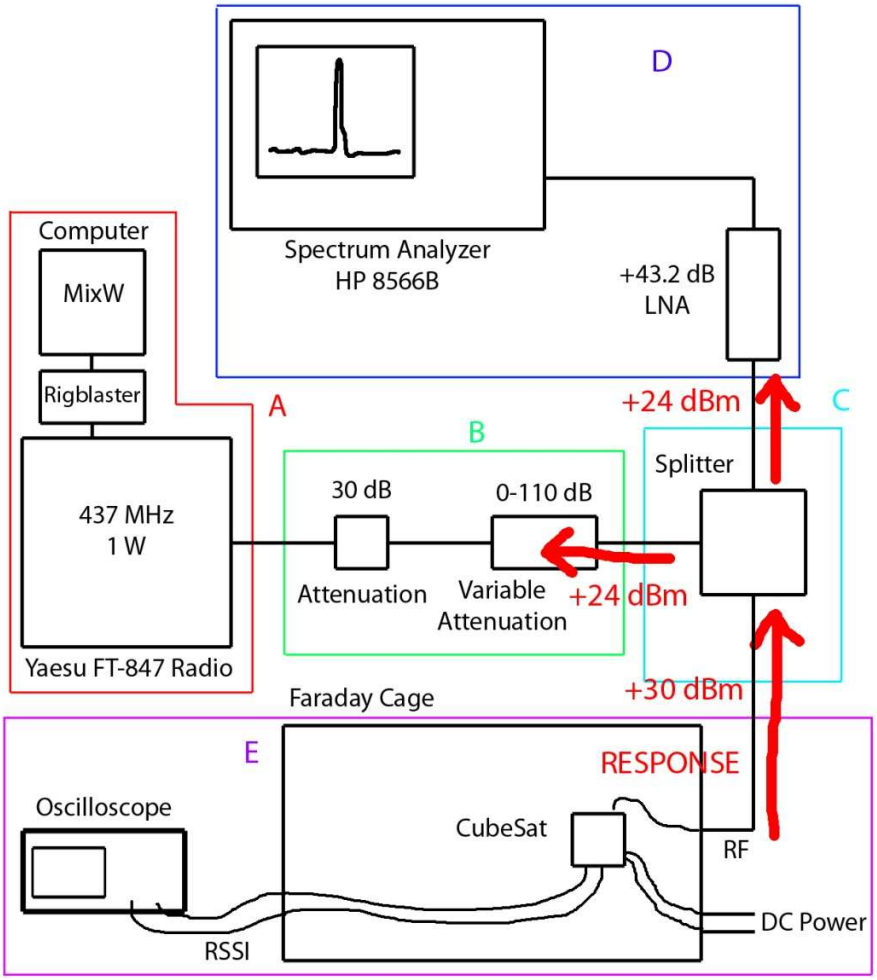


Figure 42 - Sensitivity Measurement setup during a satellite response to a command. The PolySat COMM system (Section E) outputs 1W (+30 dBm) and the resistive splitter (Section C) only offers 6 dB port to port isolation. A signal of +24 dBm will permanently damage the LNA attached to the Spectrum Analyzer (Section D).

The power splitter (discussed in Section 4.5) is a resistive splitter, so the port to port isolation is only 6 dB. During a satellite response, the input power to the LNA (Section D of Figure 42) will be approximately +24 dBm. This exceeds the maximum input power to the LNA, and would cause permanent damage [20]. To prevent damaging the LNA during sensitivity testing of the

PolySat COMM system, the LNA amplifier is disconnected from the setup (Figure 43). This setup is the standard setup used to measure sensitivity (shown in Figure 12 and Figure 42).

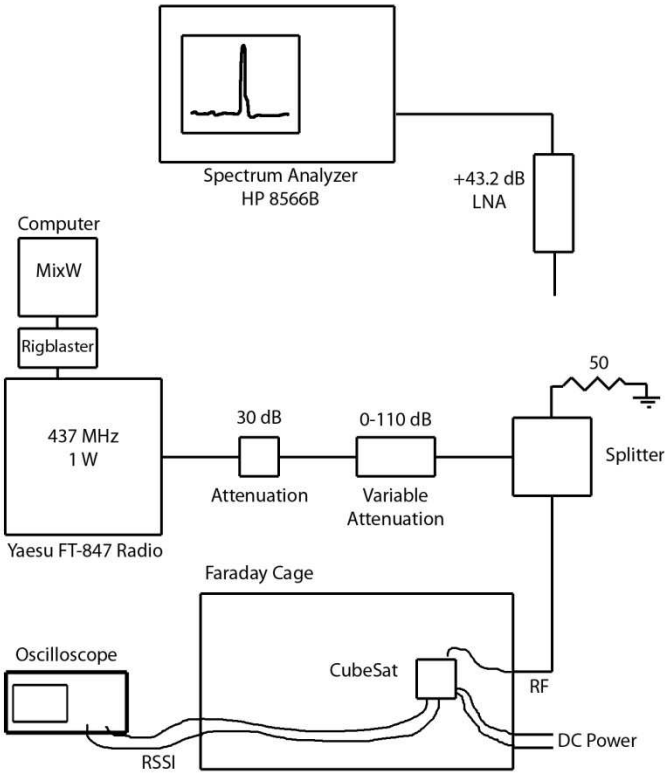


Figure 43 - Sensitivity setup for finding the threshold of sensitivity of the PolySat COMM system. The LNA is disconnected from the power splitter because the satellite response exceeds the maximum input power of the LNA and would cause permanent damage.

Once the LNA is disconnected from the splitter (Figure 43), the user can send commands while increasing the variable attenuator (Section B of Figure 12). Eventually the signal will be reduced below the sensitivity of the PolySat COMM system, and the threshold of sensitivity will be the point at which the COMM system can no longer decode the commands from the Yaesu FT-847 (Section A of Figure 12). An example sensitivity test is shown in Figure 44.

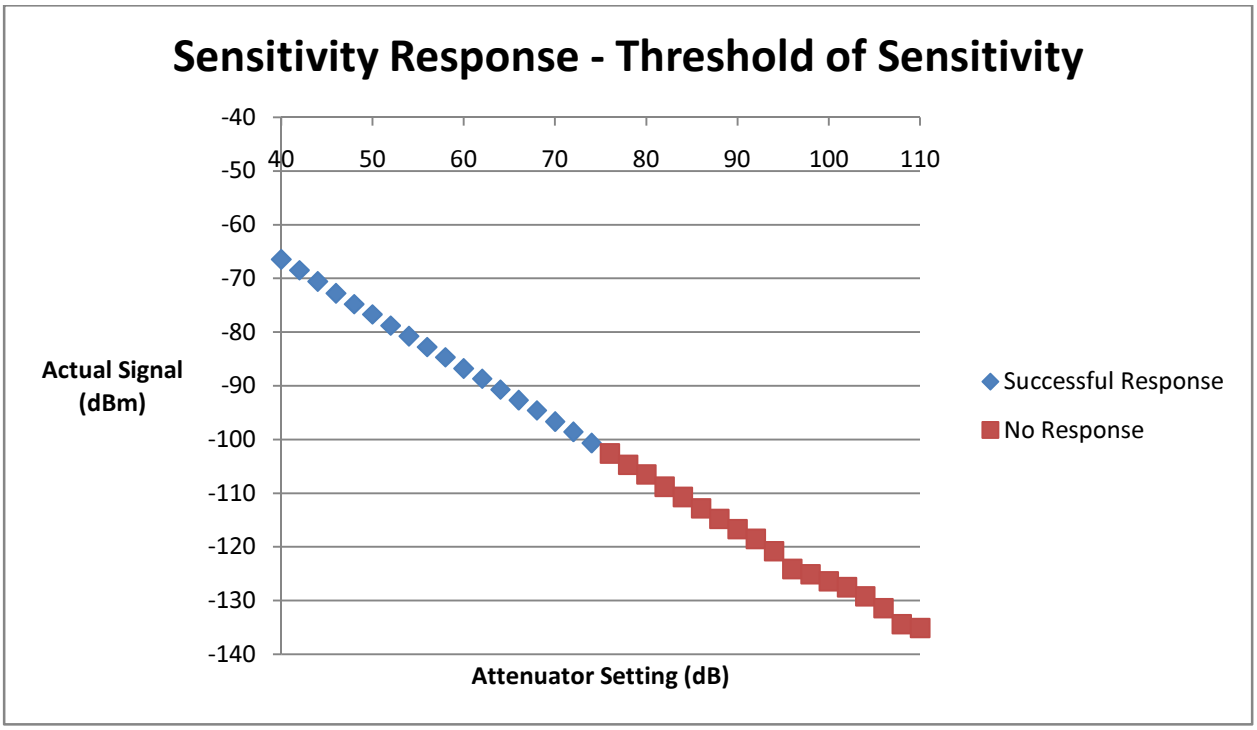


Figure 44 - Sensitivity test of the PolySat COMM system. The sensitivity threshold is -100.7 dBm, corresponding to the last successfully decoded command (indicated by a satellite response).

Once the threshold of sensitivity of the PolySat COMM system is found, the LNA and Spectrum Analyzer (Section D of Figure 42) can be reconnected to the sensitivity test setup as shown in Figure 45.

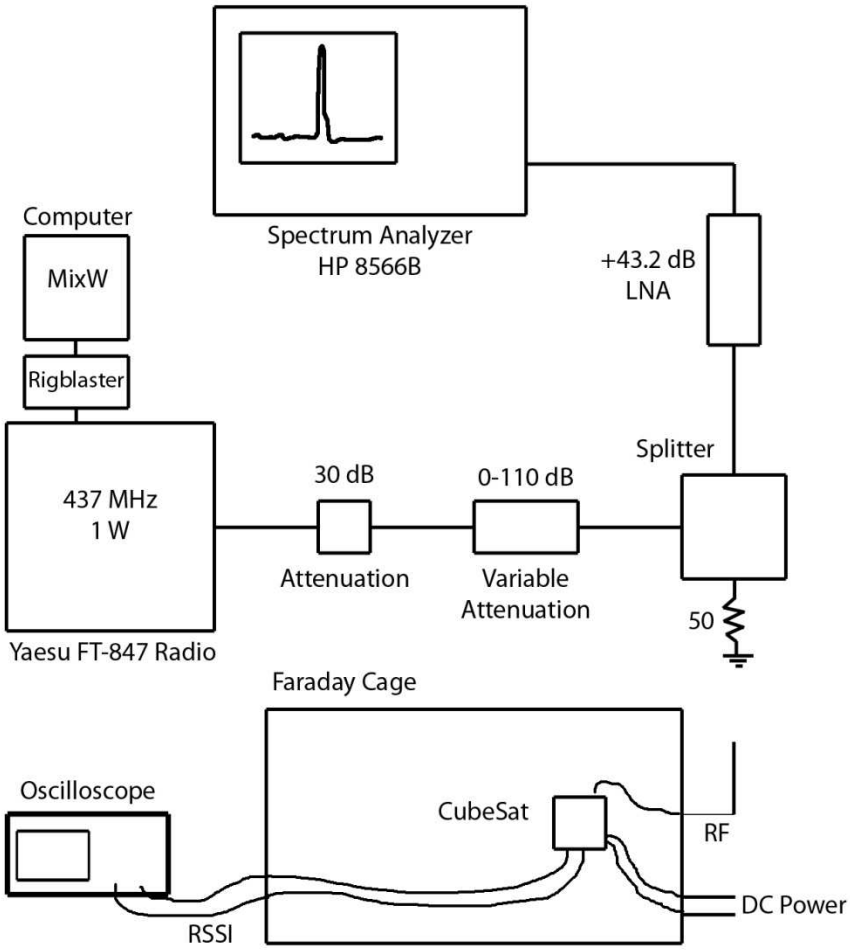


Figure 45 – Sensitivity measurement after the threshold of sensitivity is found. The LNA is used to verify the signal strength of the Minimum Detectable Signal (MDS), which is the weakest signal the PolySat COMM system is capable of responding to. This is the measured receive sensitivity and is accurate to +/-2 dB.

With the LNA and Spectrum Analyzer connected to the sensitivity test setup as shown in Figure 45, the LNA is used to verify the signal strength (dBm) of the minimum detectable signal, establishing a measured receive sensitivity of the PolySat COMM system.

Chapter 5. Sensitivity Testing

5.1 PolySat Satellite COMM System

To evaluate the COMM performance of the satellites in orbit, the receive sensitivity of the PolySat COMM systems of CP3/CP4 and CP6 were measured.

5.1.1 Overview of COMM Setup

Starting with CP2, a standardized bus was developed. Chris Day and Derek Huerta's theses [2] [3] discuss the entire system in great detail. For the scope of this project, only a brief description of the PolySat COMM system is necessary. The satellite features redundant COMMS to protect against hardware failure. Each COMM consists of several main components: CC1000 transceiver, RF amplifier, RX/TX switches, and an antenna jack.

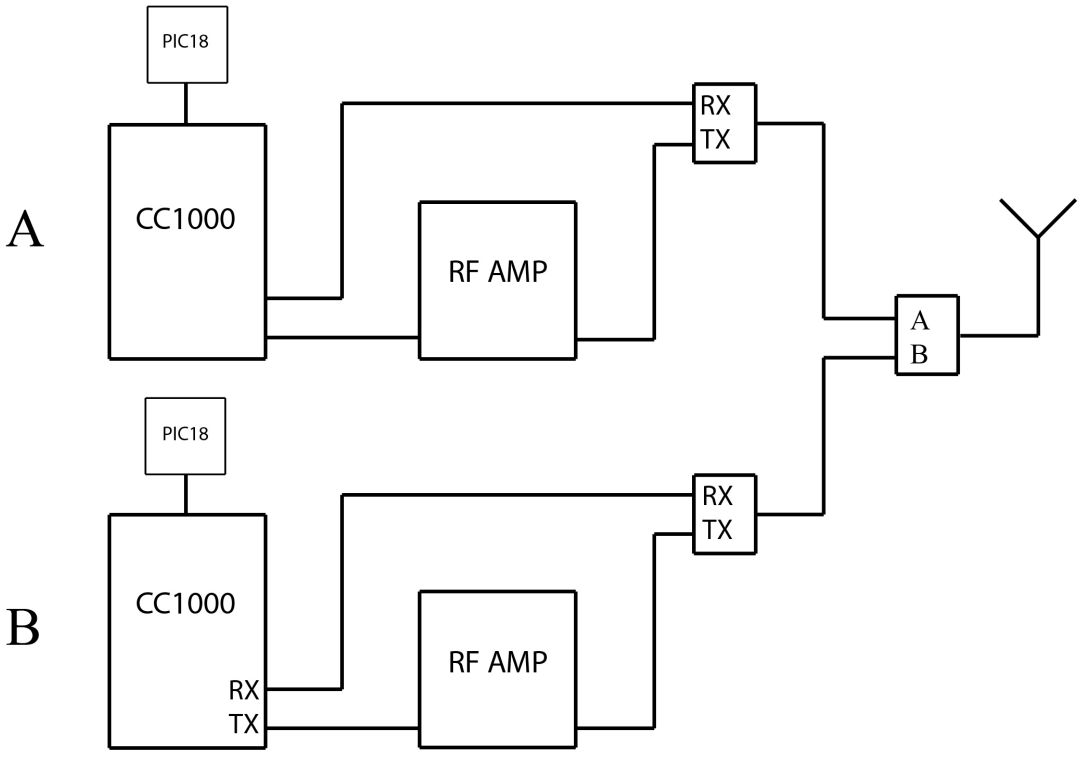


Figure 46 - Main components of the redundant COMM system. CC1000 Transceiver on left, with RF amplifier on right. Most of the additional components are supporting circuitry for the transceiver and amplifier (matching, power decoupling, etc). Each redundant COMM is labeled A and B.

Two different revisions of the CP Bus COMM system were tested. CDH Rev 4 is the COMM system flown on CP3, launched in 2007. CDH Rev 5, flown on CP6 in 2009, contains a Low Noise Amplifier on the receive line of each COMM. Bryan Klofas documented the addition of the LNA in his senior project [4]. For the remainder of this paper, Rev 4 refers to the CDH without the preamplifier, and Rev 5 refers to the CDH with the preamplifier.

5.1.2 CC1000 UHF Transceiver

The CC1000 is a single chip UHF transceiver designed for low power applications. Mainly intended for Short Range Devices (SRD) in the Industrial, Scientific, and Medical (ISM) bands, it can be programmed for operation from 300-1000 MHz [8].

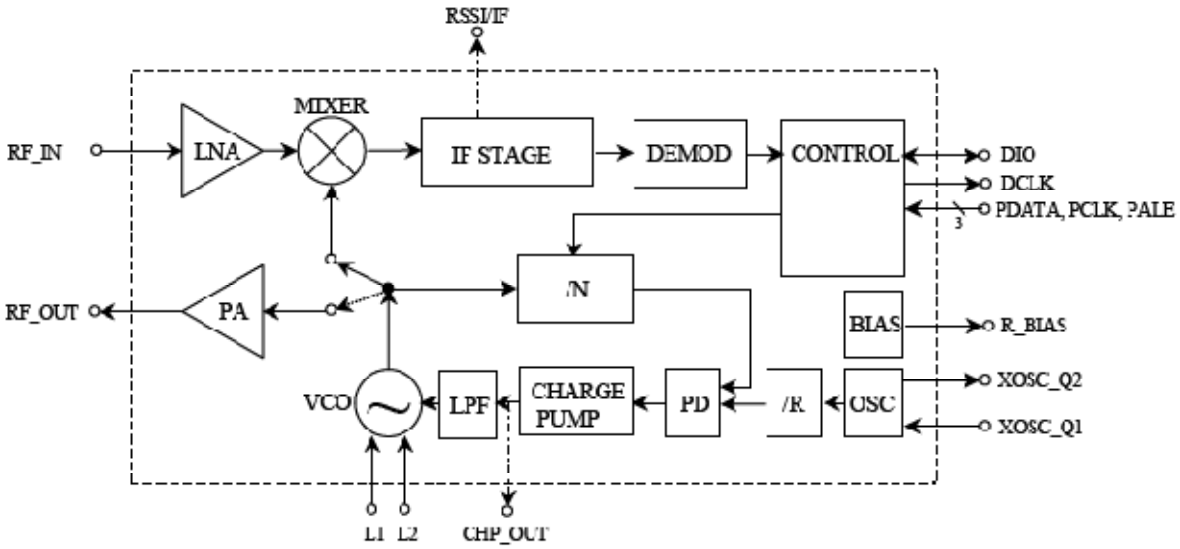


Figure 47 - High level circuit diagram of the CC1000

In receive mode, the CC1000 is configured as a traditional superheterodyne receiver. The RF signal is amplified by an LNA, and mixed down to the 150 kHz Intermediate Frequency (IF) stage for filtering and demodulation. Although not explicitly stated in the datasheet, it is implied that the LNA is broadband (300-1000MHz) and no filtering occurs until the IF stage. The

Receive Signal Strength Indicator (RSSI) is determined by measuring the raw power (independent of modulation format) at the IF stage. Two main control lines, DIO and DCLK, interface to a microcontroller for the exchange of demodulated digital data. The frequency synthesizer, used to set the LO and RF output frequencies, consists of a Phase Lock Loop (PLL) [8]. The PLL uses a 14.7456 MHz crystal oscillator as a reference.

5.1.3 Receive Sensitivity versus Frequency Separation and Data Rate

The receive sensitivity of the CC1000 is a function of several variables: frequency, data format, data rate, and Frequency Shift Keying (FSK) frequency separation. Before a conclusion on the performance of the transceiver can be made, the typical or expected performance must be gleaned from the datasheet. For many of the possible configurations, the expected receive sensitivity is listed in tabular form in the datasheet. With the PolySat COMM system utilizing the 433 MHz band and using Non Return to Zero Inverse (NRZI) encoding, the data rate and frequency separation are the final variables which determine the actual receive sensitivity [8].

Data rate [kBaud]	Separation [kHz]	433 MHz NRZ mode
0.6	64	-113
1.2	64	-111
2.4	64	-109
4.8	64	-107
9.6	64	-105
19.2	64	-103
38.4	64	-102
76.8	64	-100

Data rate [kBaud]	Separation [kHz]	433 MHz NRZ mode
0.6	20	-109
1.2	20	-108
2.4	20	-106
4.8	20	-104
9.6	20	-103
19.2	20	-102
38.4	20	-98
76.8	20	-94

Table 18 – CC1000 receive sensitivity is a function of frequency, data format, data rate, and frequency separation [8]. This table is obtained from the CC1000 datasheet. The red highlighting indicates that the uplink to the CC1000 is 600 baud data rate.

Since the COMM system of the CP Bus uses Audio Frequency Shift Keying (AFSK) rather than true FSK, the frequency separation is 2 kHz, rather than the recommended 64 kHz. Using a frequency separation of 2 kHz is not a recommended configuration of the CC1000 (the datasheet recommends for best sensitivity to keep the frequency separation as high as possible) [7] [8]. Without datasheet information for 600 baud data rate and 2 kHz frequency separation, an intuitive guess must be made. In the table above, a comparable data rate to frequency separation ratio is 4.8 kbaud and 20 kHz separation, resulting in a receive sensitivity of -104 dBm. Under this assumption, the CC1000 on the CP Bus should have a similar receive sensitivity.

5.1.4 RSSI Output

The CC1000 has a dedicated pin for Received Signal Strength Indication (RSSI). The voltage at this pin is inversely proportional to the received signal. Therefore, a voltage of 1.1V corresponds to a very weak signal (-105 dBm) and 0.1V indicates a strong signal (-50 dBm).

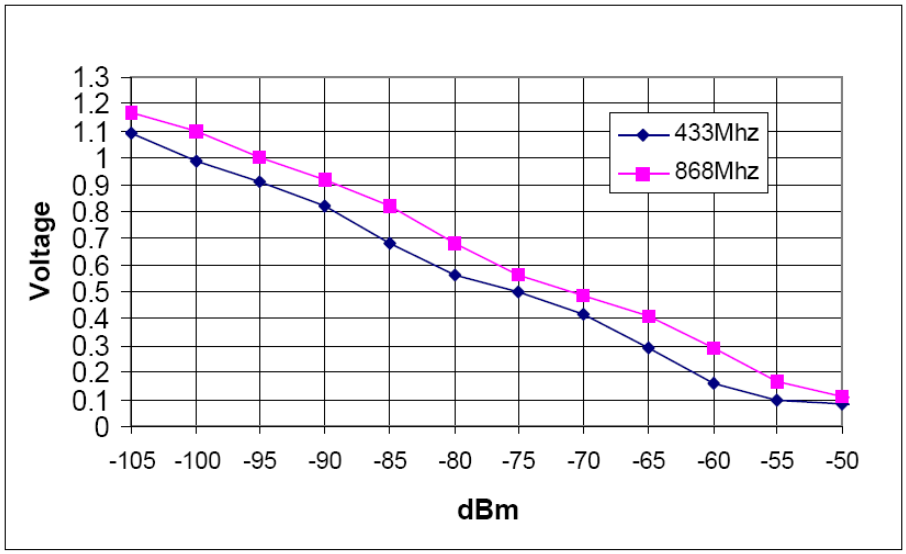


Figure 48 - CC1000 RSSI pin voltage versus receive power. This is a graph from the CC1000 datasheet, providing a reference voltage as a function of received signal strength.

The RSSI is measured at the IF stage, and only depends on the raw power, not a modulated signal with data. This was confirmed by sending both modulated and non-modulated signals and observing no difference in the RSSI. The RSSI pin of the CC1000 proved to be very useful in evaluating receiver sensitivity. First, the RSSI was monitored and compared to the magnitude of the signal reaching the isolated DUT. This is useful in discovering problems in the RF chain. Also, data collected from the RSSI pin of each COMM system was compared, providing an interesting look at what the CC1000 "sees" in terms of received power. Lastly, interference can be intentionally introduced onto the bus, while monitoring the RSSI pin. This provides information about the susceptibility to DESENS (receiver desensitization) of the CC1000, presented in Chapter 6.

5.4.3 CDH Revision 4

CDH Rev 4, flown on CP3, is the standard CP Bus (without the LNA) [2] [3]. The RF chain is shown in Figure 49. RF switches are used to select each COMM, and for switching between Rx/Tx for the antenna.

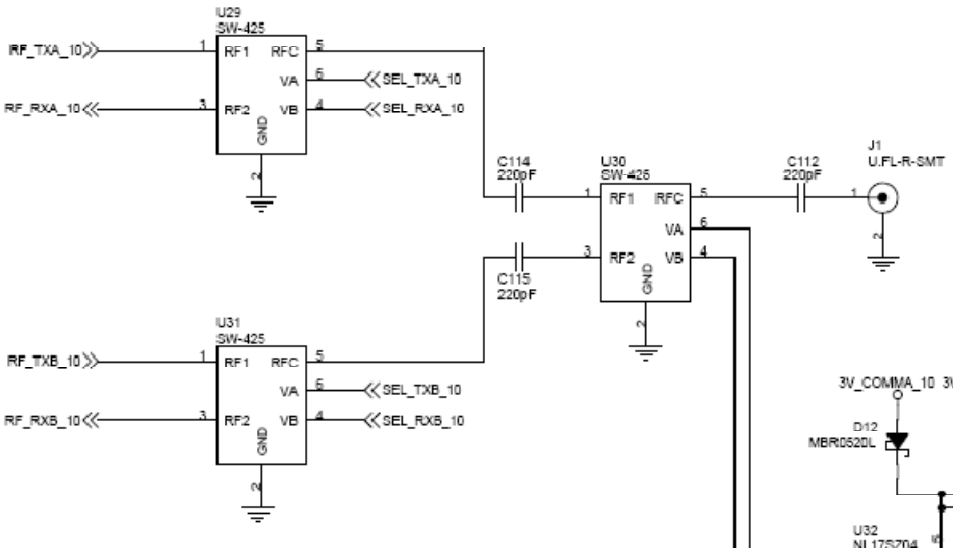


Figure 49 – RF Chain of CDH Rev 4. The antenna connector is AC coupled to the main RF switch, which selects COMM A or B. Individual RF switches select between RX and TX. The RX line goes directly to the CC1000, and the TX is from the RF amplifier output.

5.4.4 CDH Revision 5

CDH Rev 5 is the most current CDH. Past revisions from 2-4 have included mostly minor layout changes, such as fixing wire modifications, and replacing obsolete components. The CC1000's noise figure is 12 dB, which is pretty poor. By adding a gain block to the front, such as an LNA, the sensitivity can significantly be improved (theoretically). With CDH Rev 5, an LNA was added to the receive line. The required matching elements were added, along with a high pass filter [4].

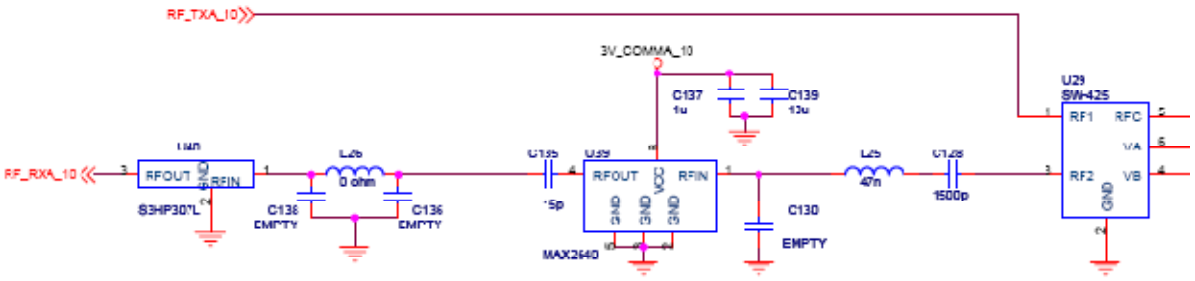


Figure 50 – RF Chain of COMM A on CDH Rev 5. The only difference is the addition of an LNA, associated matching network, and high-pass filter.

Comparing CDH Rev 5 (Figure 50) to CDH Rev 4 (Figure 49), the differences on the receive line include the LNA, matching elements, and a high-pass filter.

5.2 COMM Sensitivity Testing

5.2.1 Overview of Testing

Using the sensitivity test set-up developed (shown in Figure 12), the receive sensitivity of both CDH Rev 4 and Rev 5 boards was measured. During CP2 and CP6 development, only estimates of sensitivity could be made [4], so a direct measurement is a huge step forward in gauging performance of the COMM system. Comparing sensitivity measurements to the expected performance of the CC1000, the actual performance of the transceiver can be evaluated. Directly comparing the measured sensitivity between CDH revision 4 and 5 shows the increase in sensitivity due to the LNA. For both revisions, the sensitivity of COMM A and B were individually measured. The Yaesu FT-847 transceiver, utilized during satellite passes, was also tested for receive sensitivity.

5.2.2 CDH Testing – Measuring the Receive Sensitivity

Following the procedure developed for testing receive sensitivity, the CDH boards were tested for receive sensitivity. The testing procedure for measuring receive sensitivity of the PolySat COMM system (CDH Rev 4 and 5) is outlined in Section 4.11 and detailed in Appendix A. Both COMMA and COMMB (Figure 46) were measured for comparison. The results of the sensitivity measurements of CDH Rev 4 and Rev 5 are shown in Sections 5.2.3 and 5.2.4.

5.2.3 CDH Rev 4 – Measured Sensitivity Testing

The CDH Rev 4 used for sensitivity testing was from CP3 TestSat, a model of the CP3 in orbit used for bench testing. Due to hardware shortages in the lab, only one CDH Rev 4 was available for testing.

CDH Rev 4 Sensitivity	
COMMA	-88.5 dBm
COMMB	-92.4 dBm

Table 19 – The measured sensitivity of CDH Rev 4 for both COMMA and COMMB, tested using the sensitivity measurement setup in Section 4.11

An interesting thing to note in Table 19 is that COMMB outperforms COMMA by almost 4 dB. From on-orbit data, it has been noted that COMMB performs better than COMMA. The RSSI pin of each COMM was monitored, allowing verification of the signal strength received. The resting RSSI value (Table 20) is the RSSI output from the CC1000 with a 50Ω termination at the antenna input of the CDH being tested (Figure 46).

Resting RSSI and Signal Strength		
COMMA	0.909 V	-95 dBm

COMMB	0.997 V	-100 dBm
Expected	1.1 V	-105 dBm

Table 20 –Resting RSSI of CC1000 of CDH Rev

With a 50Ω termination at the antenna input, the CC1000 "resting RSSI" values indicate residual noise on the CDH. From the testing, it seems that the COMM with the lower "resting RSSI" typical outperformed the other COMM.

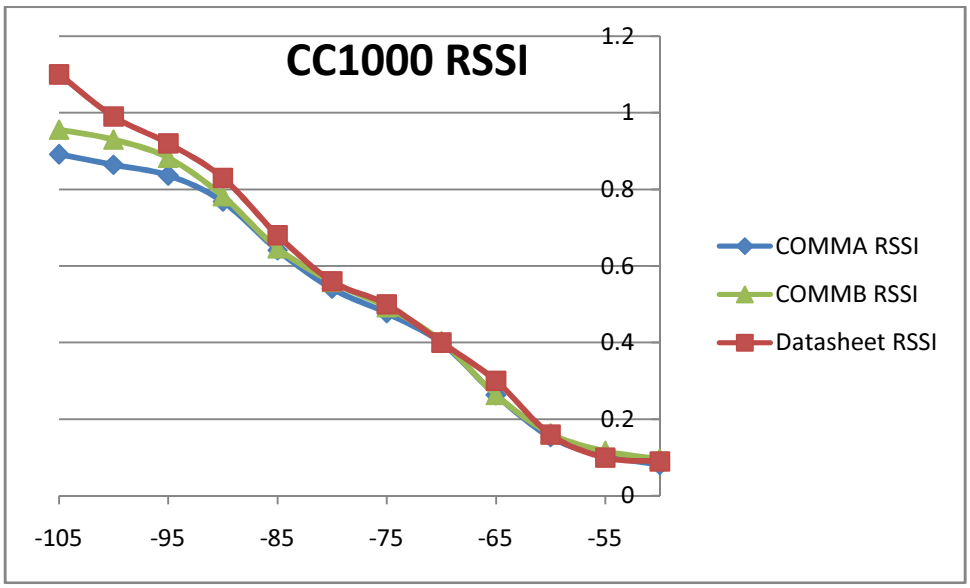


Table 21 - RSSI Characterization of CDH Rev 4

The RSSI values correspond closely to the datasheet until the signal strength drops below approximately -80 dBm.

5.2.4 CDH Rev 5 – Measured Sensitivity Testing

The CDH Rev 5 used for testing was one of the several boards assembled as flight candidates for CP6. Additional sensitivity data was obtained by testing a flight candidate board

built for CP5, a satellite testing a de-orbiting mechanism. CP5 is currently under development, allowing time for possible COMM system upgrades for improved sensitivity.

CDH Rev 5 Sensitivity	
COMMA	-94.4 dBm
COMMB	-101.9 dBm

Table 22 - Sensitivity of CDH Rev 5 (with preamp), tested using the sensitivity measurement setup in Section 4.11

There is a significant difference between COMMA and COMMB, as COMMB is 7.5 dB more sensitive. A possible reason for this is discussed in Section 6.1.1. By observing the RSSI value with a 50Ω termination at the input of the CDH, dubbed the "resting RSSI", any large deviation from the expected indicates noise seen by the CC1000.

Resting RSSI and Signal Strength		
COMMA	0.775 V	-85 dBm
COMMB	0.998 V	-100 dBm
Expected	1.1 V	-105 dBm

Table 23 - Resting RSSI of CDH Rev 5

Table 23 shows the CC1000 of COMMA detects signal strength of -85 dBm even with a 50Ω termination at the antenna jack. The CC1000 of COMMB detects signal strength on the order of -95 dBm, corresponding closer to the performance of CDH Rev 4 (Section 5.2.3). As seen in CDH Rev 4, the COMM with the lower resting RSSI performed better.

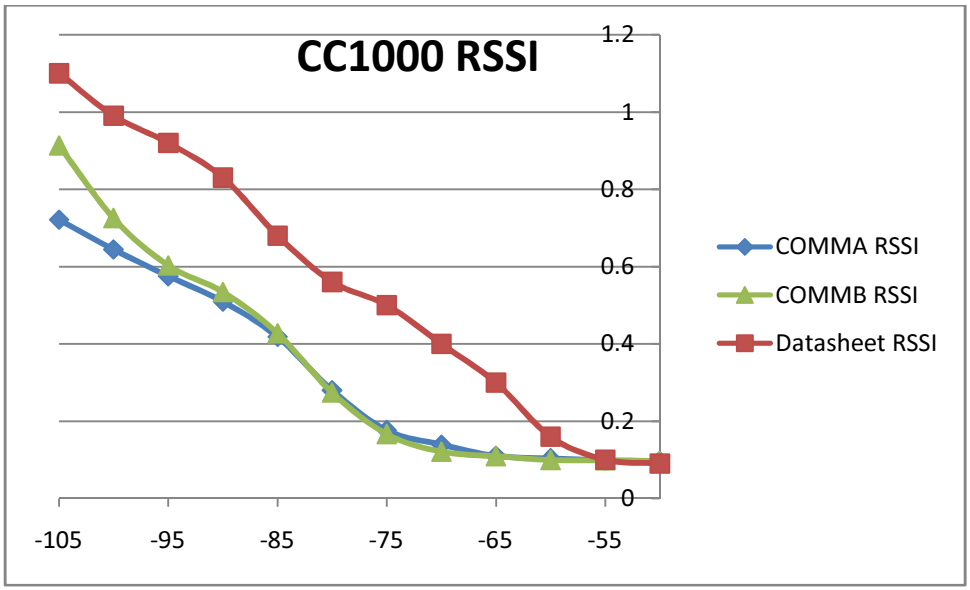


Table 24 - RSSI from both COMMS of CDH Rev 5 compared to datasheet.

5.2.5 CP5 CDH Flight Candidate

CP5 will utilize the CDH Rev 5 board. One of the flight candidate boards was recently completed, providing the opportunity to characterize another board. The performance of the board is shown below.

CDH Rev 5 Sensitivity	
COMMA	-96.8 dBm
COMMB	-100.5 dBm

Table 25 - CP5 Flight Candidate, receive sensitivity performance

COMMA performs better than the other CDH Rev 5 candidate, showing that manufacturing differences may be causing differences in sensitivity.

Resting RSSI and Signal Strength		
COMMA	0.890V	-90 dBm

COMMB	0.953V	-95 dBm
Expected	1.1 V	-105 dBm

Table 26 - CP5 Flight Candidate, resting RSSI values

Again, the COMM with lower "resting RSSI" performs better. With a lower residual noise, the SNR will be greater, possibly explaining the better performance. It is very interesting that the sensitivity performance varies between each board, implying that multiple flight candidates should be tested to determine the best performing board.

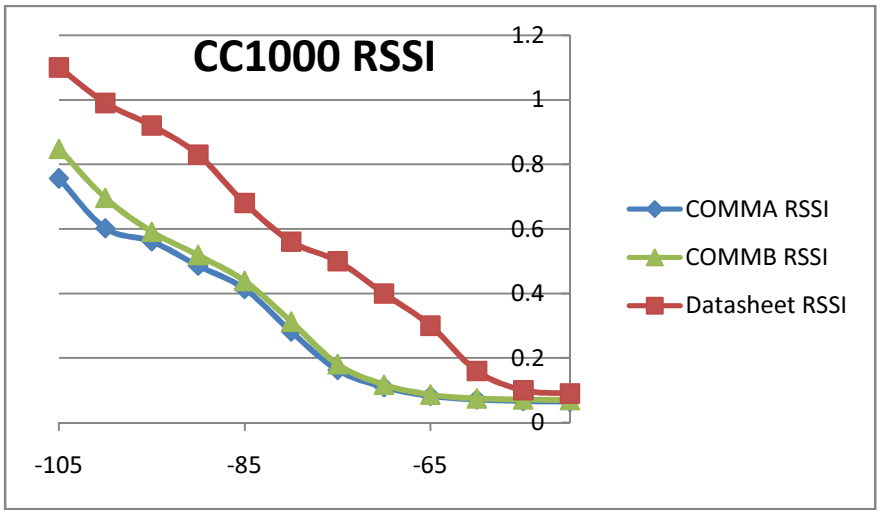


Figure 51 – CP5 Flight Candidate RSSI curve

5.2.7 Yaesu FT-847 Transceiver

PolySat has two independent ground stations named Marconi and Hertz. The rotor mounted Yagi antennas can be seen atop the roof of the ATL. Marconi consists of a Yaesu FT-847 amateur transceiver connected to dual-phased M-squared 436CP42Yagi antennas. A preamp is connected directly to the antenna with LMR-400 coax, which is fed through the roof with a 50 ft section of 5/8" heliax to the Yaesu FT-847 radio [6]. With the CC1000 characterized, its performance can be judged by comparing it to the ground station receiver. By reversing the

standard receive sensitivity test, the Yaesu FT-847 can be characterized. The reversed sensitivity test is shown in Figure 52. The earlier discussion of antenna reciprocity (in Section 3.2.1) suggested that the inconsistent uplink issues could be caused by significant sensitivity differences in the two receivers. Since downlinks can be reliably decoded, a significant difference in sensitivity between both receivers would suggest a more sensitive receiver is required for the PolySat COMM system. From the user's manual, the FT-847 has a stated sensitivity of 0.125μV at the 430MHz band with a 10 dB SNR [21]. This is shown in Equation 9.

$$\frac{(0.125\ x\ 10^{-6}\ V)^2}{50\Omega} = 312.5\ x\ 10^{-18} W = -125\ dBm$$

Equation 9 – Calculating the expected receive sensitivity of the Yaesu FT-847. The datasheet states that the minimum sensitivity is 0.125 μV, so the minimum sensitivity in power (dBm) can be calculated.

The filter width of the SSB is 2.2kHz, so the thermal noise seen can be calculated (Equation 10).

$$-174\ dBm/Hz + 10\log_{10}(2200) = -140.6\ {}^{dBm}/_{2200Hz}$$

Equation 10 - Calculating the thermal noise of the Yaesu FT-847 receiver in Single Side Band (SSB)

With a theoretical noise floor at -140 dBm and a 10 dB SNR at -125 dBm, measuring the receiver sensitivity will provide a good baseline comparison to the CP Bus COMM system. To test the sensitivity, the testing procedure was reversed: TestSat, now the RF source, was programmed to beacon every 30 seconds, providing packet information for the Yaesu Transceiver to decode. Attenuation was increased to reduce the signal received by the Yaesu transceiver. Once MixW (Figure 12) could no longer decode the beacon packets, the signal strength was measured using the LNA and Spectrum Analyzer (at the last attenuation setting MixW could properly decode packets).

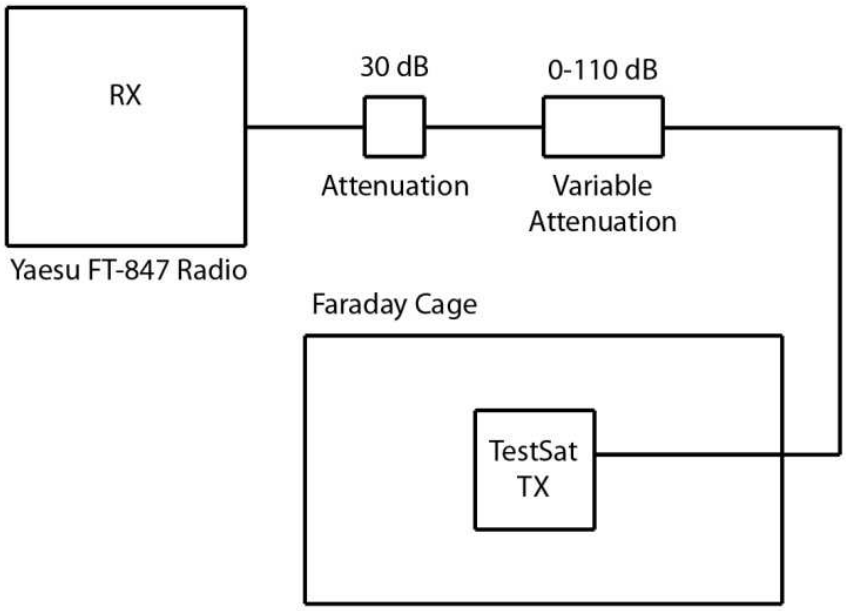


Figure 52 - Test Setup to measure the receive sensitivity of the Yaesu FT-847 ground station receiver. The satellite is set to transmit every 30 seconds, providing the Yaesu FT-847 data packets to receive and decode. By adjusting the variable attenuator, the signal strength to the FT-847 was reduced until it could no longer decode packets, providing a threshold of receive sensitivity.

The Yaesu radio successfully decoded packets down to -115 dBm, indicating that the Yaesu radio outperforms the CDH Rev 5 by about 15 dB. It outperforms CDH Rev 4 by approximately 25 dB. In order to consistently close the uplink margin, the CP Bus needs a more sensitive receiver.

Chapter 6. Additional Testing

As an attempt to dig deeper into the sensitivity issue, several additional tests were performed to explore possible explanations of reduced sensitivity. After determining the receive sensitivity, the Spectrum Analyzer was used to observe noise levels at the receive line of the CC1000. Each COMM of both CDH boards was compared, with the CC1000 development board used as a baseline standard. More specific tests were conducted to confirm or disprove theories speculating the cause of poor receive sensitivity. The bus was tested with and without I^2C and DC-DC converters, which are switching elements believed to be introducing noise on the bus. These tests were performed on both Rev 4 and Rev 5 CDH boards.

6.1 Receiver Noise Floor Comparison

The noise floor of each system was measured using the test setup shown in Figure 53. This was done by placing each COMM system (CC1000 Development board, CDH R4, and CDH R5 boards) in the Faraday Cage (for isolation from outside noise) and using the LNA to amplify any noise seen at the antenna connection (the receive line of the CC1000, Figure 49 and Figure 50).

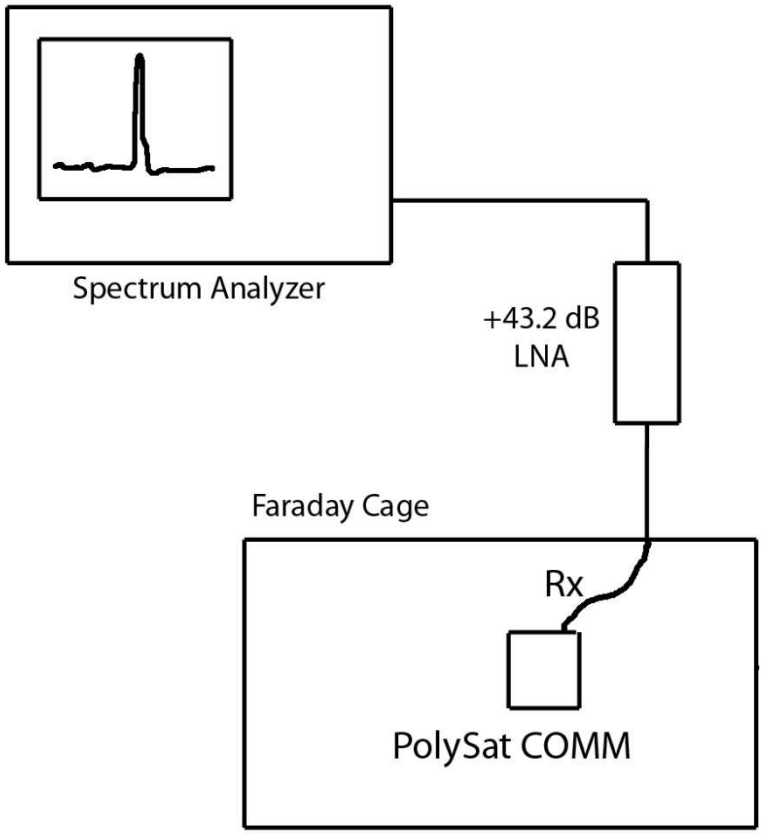


Figure 53 – Test setup to monitor the noise at the receive line of the PolySat COMM system. The LNA attached to the Spectrum Analyzer is used to observe the noise floor.

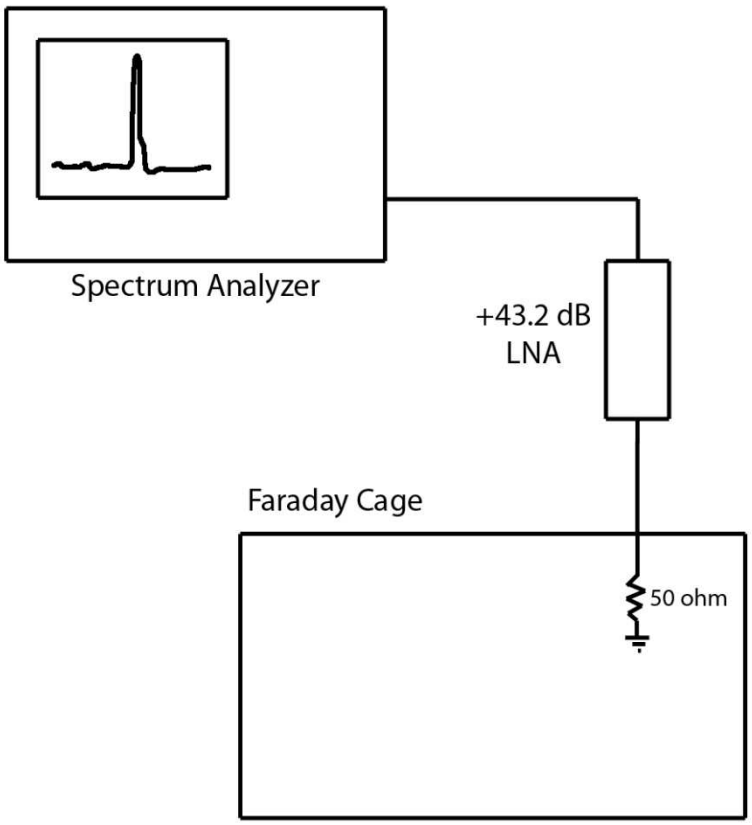


Figure 54 - Test setup showing the system noise floor of the LNA and Spectrum Analyzer. This is important in comparisons between the measured noise of each COMM system.

For comparison, the system noise floor (setup shown in Figure 54) is included. It is important to note that each graph obtained from the noise floor is 42.3 dB higher than the actual signal, due to the gain of the LNA. However, since all measurements include this gain, it's not necessary to subtract off this gain. A high gain stage in front of the Spectrum Analyzer (Figure 54) is required to increase sensitivity of the Spectrum Analyzer (discussed in Section 4.7). Before diving into a discussion of the noise performance, LO leakage should be mentioned to reduce confusing normal LO leakage for noise on at the receive line of the CC1000.

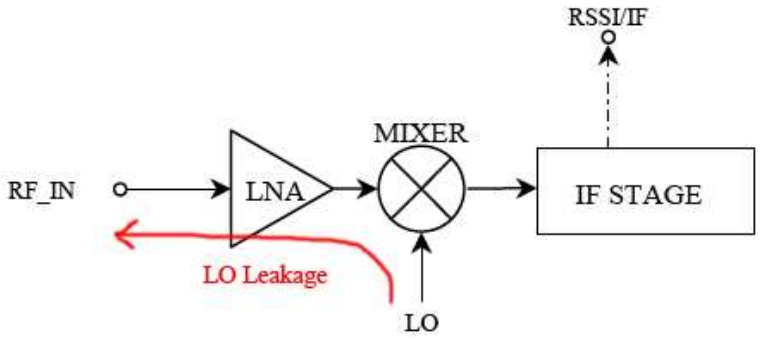


Figure 55 – LO leakage. For the CC1000 transceiver, the leakage is -57 dBm.

In a superheterodyne receiver, the RF signal is mixed down to the IF with the LO. A non-ideal mixer exhibits LO leakage, which is when the LO signal leaks backwards to the RF input (or also to the IF port). Since the IF of the CC1000 is 150 kHz, the LO leakage is a weak signal (-58 dBm) 150 kHz away from the RX frequency. LO leakage, common in all receivers, is important to note (otherwise it could be mistakenly identified as noise on the PolySat COMM system).

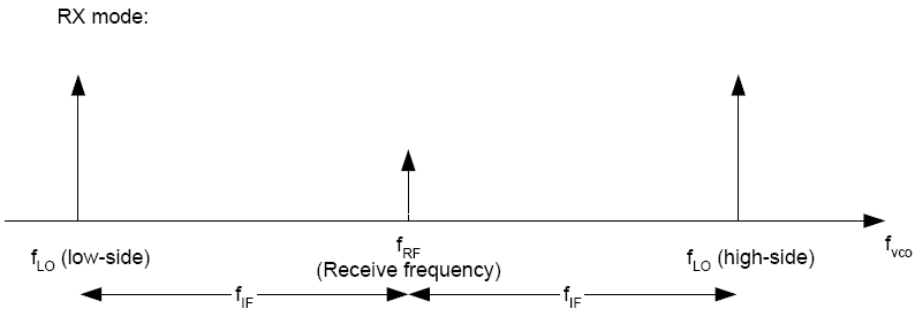


Figure 56 – The LO will be 150kHz above the RX frequency for high-side injection, and 150 kHz below RX for low-side injection.

For the CDH Rev 4 and 5, with high-side LO injection, the LO leakage occurs at 437.515MHz. The CC1000 development board, programmed at 434.010 MHz, utilizes low side injection, so the LO leakage is at 433.860 MHz.

6.1.1 Receive Line of CC1000 – Noise Floor at RX/TX Frequency

The first test performed was a comparison of the different COMMs at the receive frequency of interest. For the CDH boards, this was 437.365 MHz. The CC1000 development board was set to 434.010 MHz. By using a small span of 1MHz, noise at the receive frequency could be compared. The CC1000 development board provides an excellent baseline standard to compare the CDH COMMs to.

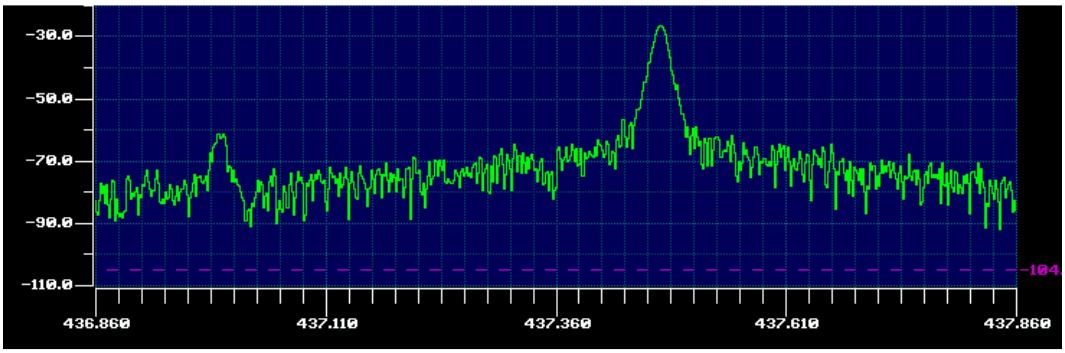


Figure 57 - CDH R4 CommA noise floor, centered at the PolySat COMM receive frequency 437.365 MHz. LO leakage visible at 437.515 MHz. RBW 10 kHz. Crystal harmonic also visible.

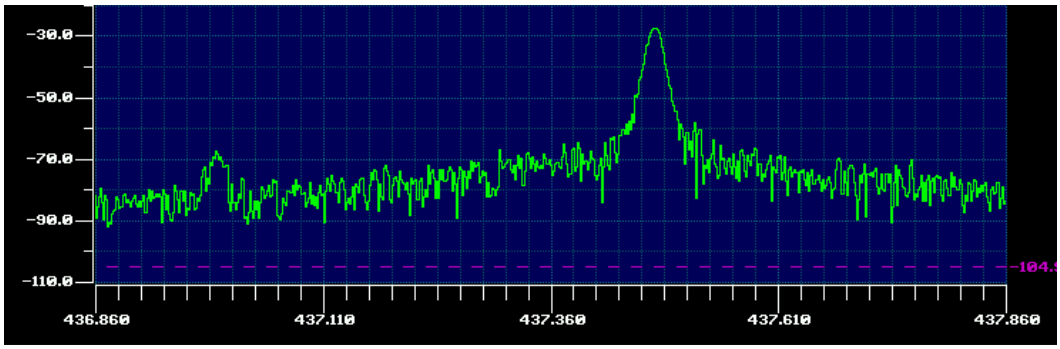


Figure 58 - CDH R4 CommB noise floor, centered at the PolySat COMM receive frequency 437.365 MHz. LO leakage visible at 437.515 MHz. RBW 10 kHz

Both COMMA (Figure 57) and COMMB (Figure 58) have very similar noise characteristics, but COMMB has slightly lower noise. In receive mode, both COMMs measure around -70 dBm at the RX frequency of 437.365 MHz, comparing closely to the noise of the development board at the RX frequency of 434.010 MHz (Figure 59).

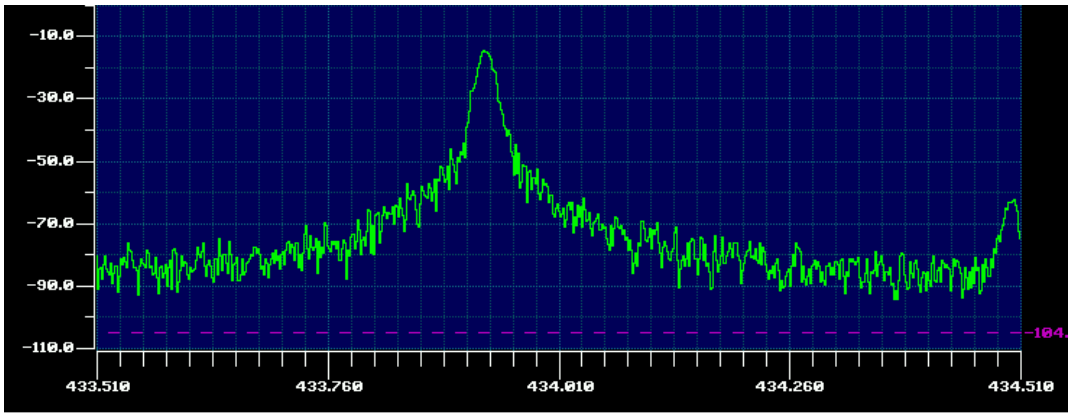


Figure 59 - CC1000 Development Board, centered at receive frequency 434.010 MHz. LO Leakage visible at 433.860 MHz, RBW 10 kHz

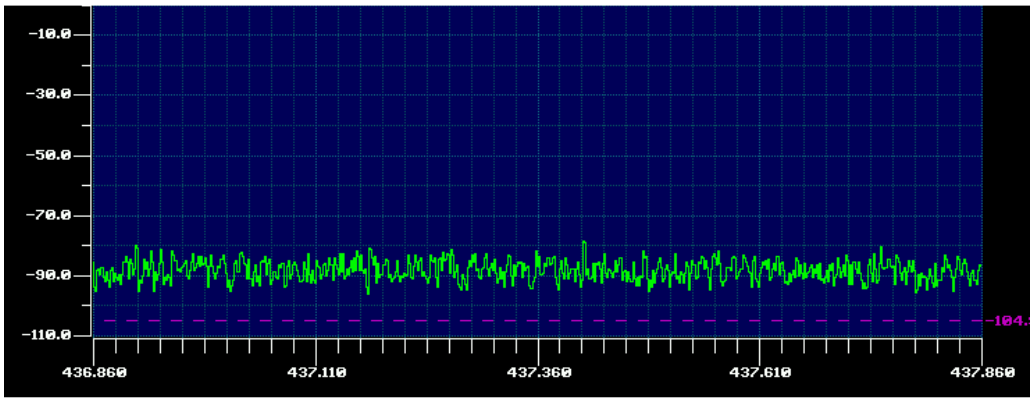


Figure 60 - System Noise Floor of the LNA and Spectrum Analyzer. RBW 10 kHz. The input of the LNA is terminated with a 50 Ω connection. This provides a reference noise level at which to compare each noise floor graph to.

COMM System	Noise at RX frequency	Comments
CDH Rev 4 – COMM A	-65 dBm	Measured sensitivity: -88.5 dBm
CDH Rev 4 – COMM B	-70 dBm	Measured sensitivity: -92.4 dBm
CC1000 Development Board	-75 dBm	Figure 59
System Noise Floor	-85 dBm	Figure 60

Table 27 – Results of the noise measurement at the RX frequency of CDH Rev 4 and CC1000 development board. The noise of COMMA at the RX frequency is 10 dB greater than the CC1000 development board, and 5 dB higher than COMMB, possible causing the difference in measured sensitivity between COMMA and COMMB.

For comparison purposes, the system noise floor is included. By terminating the LNA with a 50Ω load, the noise floor of the Spectrum Analyzer and LNA can be observed (Figure 60).

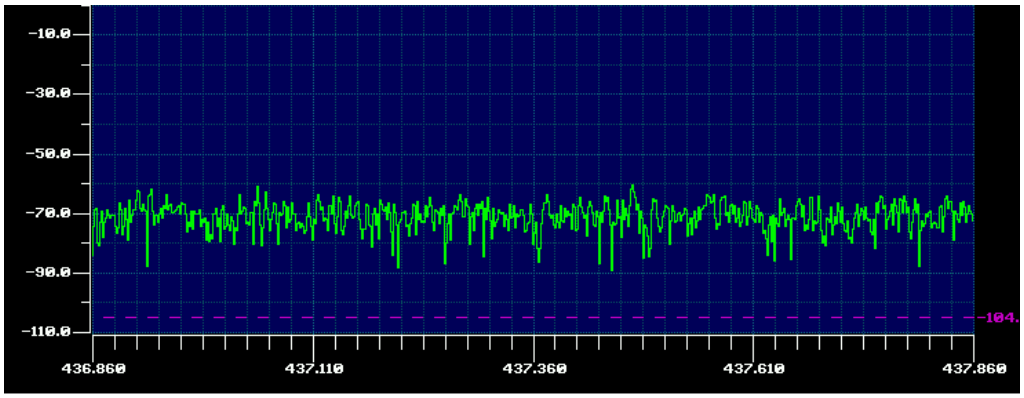


Figure 61 - CDH Rev 5, CommA, centered at receive frequency 436.365 MHz, RBW 10 Khz

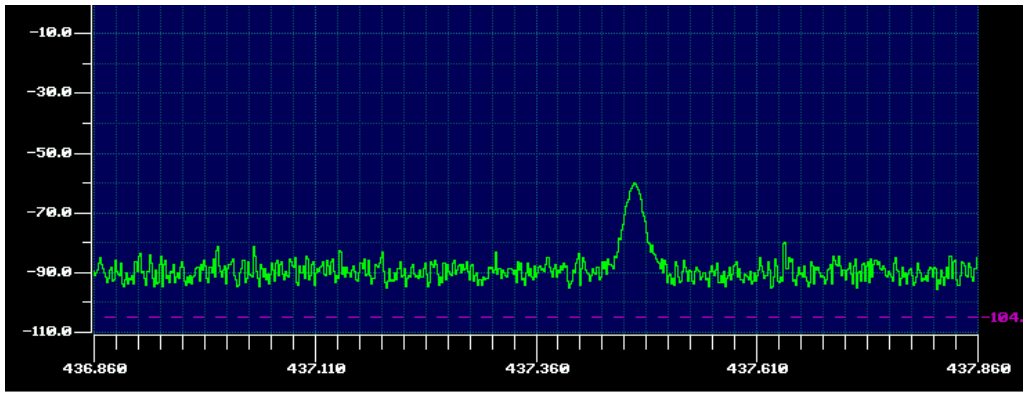


Figure 62 - CDH Rev 5, CommB, centered at receive frequency 437.365 MHz, RBW 10 kHz

COMM System	Noise at RX frequency	Comments
CDH Rev 5 – COMM A	-70 dBm	Measured sensitivity: -94.4 dBm
CDH Rev 5 – COMM B	-90 dBm	Measured sensitivity: -101.9 dBm
CC1000 Development Board	-75 dBm	Figure 61
System Noise Floor	-85 dBm	Figure 62

Table 28 – Results of the noise measurement at the RX frequency of CDH Rev 5 and CC1000 development board. The noise of COMMA at the RX frequency is 20 dB greater than COMMB, possible causing the difference in measured sensitivity between COMMA and COMMB. The S_{12} of the LNA (Figure 50) is 30 dB, reducing the LO leakage (Section 6.1) and any noise between the output of the LNA and the input to the CC1000 (Figure 50)

Recalling from the measured receive sensitivity testing (Section 5.2.3), it was noted that the measured sensitivity of CDH Rev 5 COMMB was 7.5 dB more sensitive than COMMA. Comparing the noise profiles centered at 437.365MHz of COMMA and COMMB (Figure 61 and Figure 62 respectively), a possible explanation of decreased sensitivity is that the noise floor on COMMA is almost 20 dB higher. This would reduce the SNR, resulting in a reduction of receive sensitivity. Since both COMMs are identical (hardware and software), this large increase in broadband noise is most likely attributed to layout differences.

6.1.2 Receive Line of CC1000 – Broadband Noise Floor

A PCB with poor layout typically will see an increase in broadband noise [15]. The next noise test was to see if there was broadband noise over a large span (400 MHz).

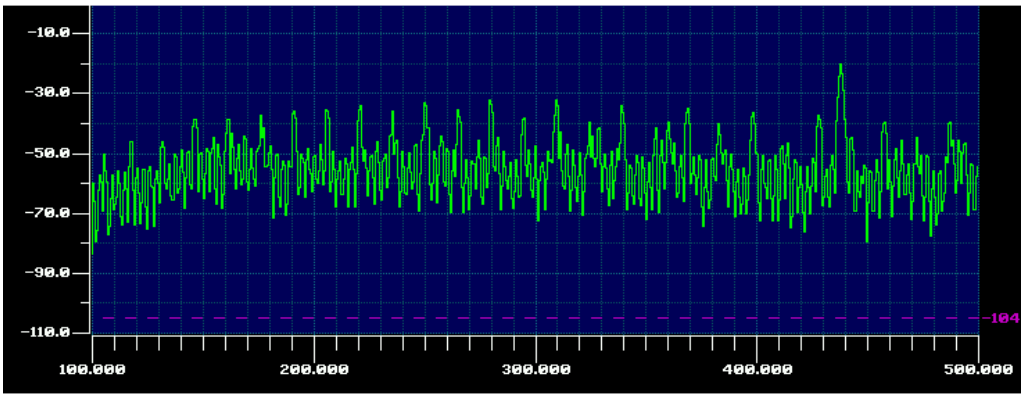


Figure 63 - CDH Rev 4 CommA, 100-500 MHz, RBW 1MHz. Harmonics of crystal spaced 14.74 MHz apart are clearly visible. Broadband noise is much higher than CC1000 development board (Figure 67)

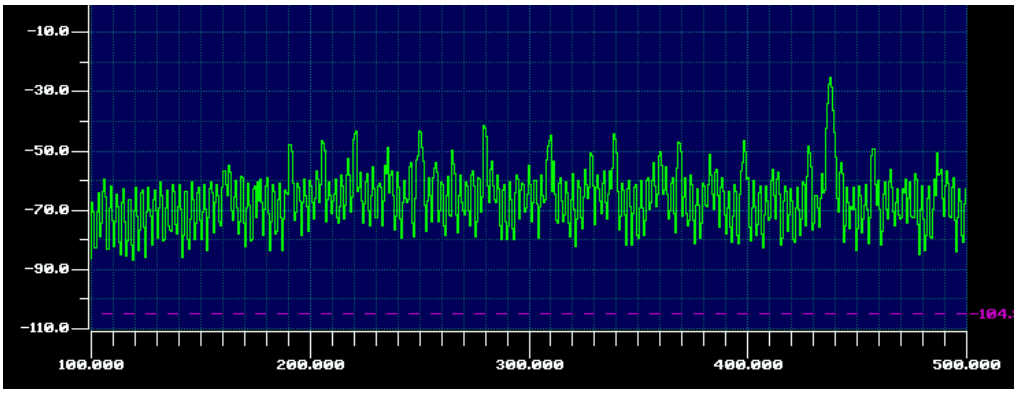


Figure 64 - CDH Rev 4 COMMB, 100-500MHz, RBW 1MHz. Harmonics of crystal spaced 14.74 MHz apart are clearly visible. Broadband noise is much higher than CC1000 development board (Figure 67)

COMMA has an overall noise floor of slightly below -50 dBm (Figure 63), with crystal harmonics reaching -35 dBm. The crystal harmonics are from the CC1000's 14.7456 MHz crystal oscillator, and are spaced apart by 14.7456 MHz. COMMB has a lower noise floor of about -60 dBm, and crystal harmonics below -40 dBm.

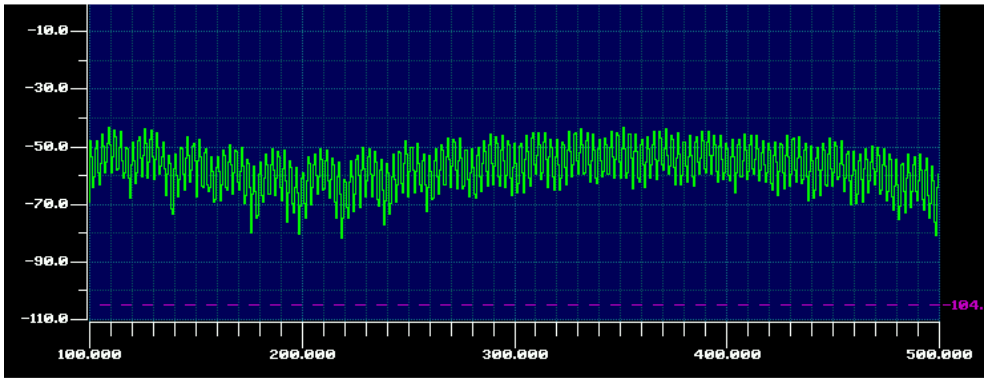


Figure 65 - CDH Rev 5 CommA, frequency span of 100-500 MHz, RBW 1MHz.

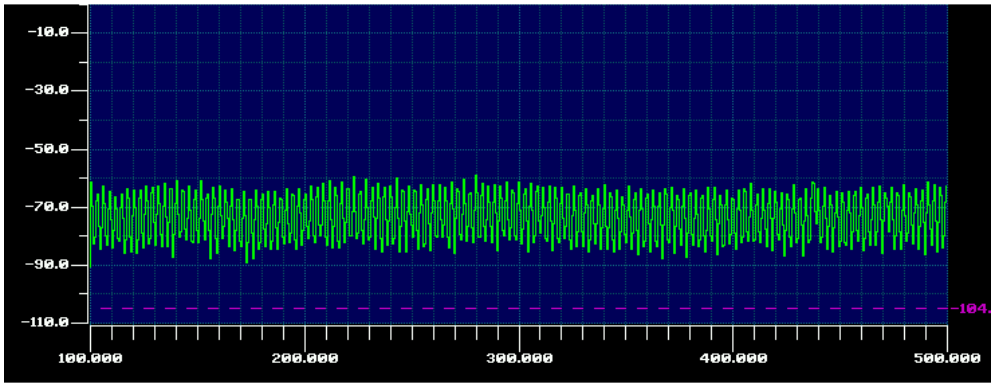


Figure 66 - CDH Rev 5, COMMB, frequency span of 100-500MHz, RBW 1MHz

The broadband noise of COMMA is typically around -50 dBm (Figure 65), but COMMB shows a much more controlled at around -65 dBm (Figure 66). While this actually performs better than the CC1000 development board (Figure 67), it's important to note that the S_{12} of the onboard LNA of CDH Rev 5 is 30 dB [4], possibly blocking a lot of that noise. The LO leakage, missing from the noise profile of COMMB in Figure 66, is also suppressed by 30 dB.

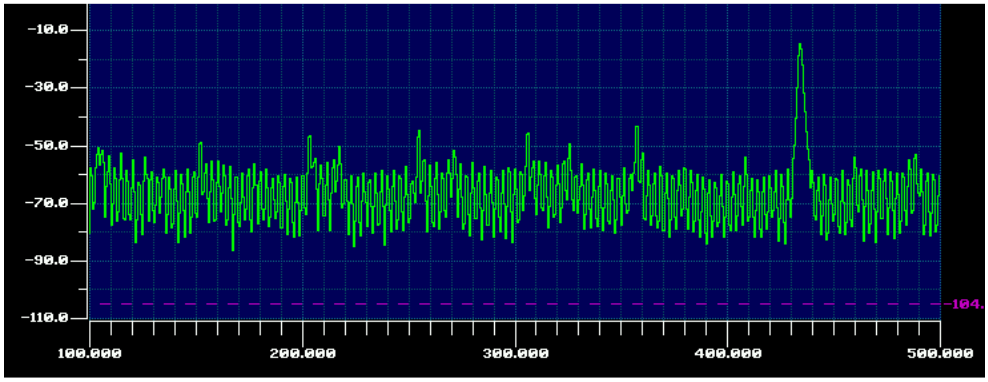


Figure 67 - CC1000 Development Board, 100-500 MHz, RBW 1MHz. Crystal harmonics repeated every 14.74 MHz, and LO leakage visible at 433.860 MHz

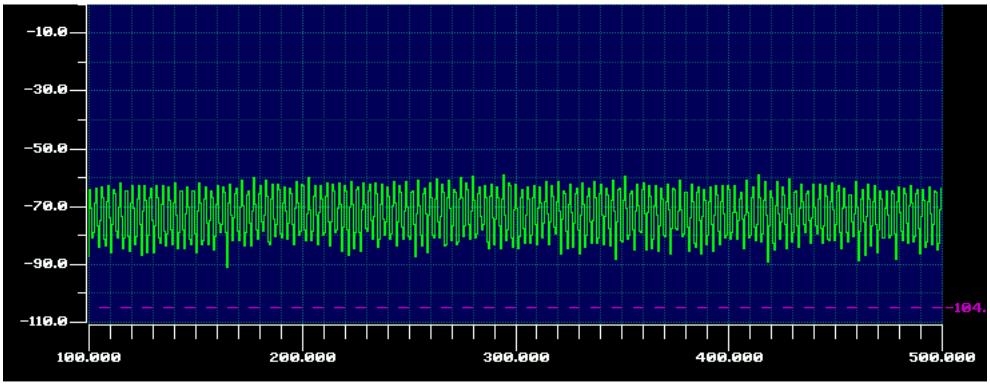


Figure 68 - System Noise Floor 100-500 MHz, RBW 1MHz (LNA and Spectrum Analyzer)

The average broadband noise of the CC1000 development board is around -60 dBm, slightly higher than the system noise floor.

1. Broadband noise was measured to be higher on CDH Rev 4 and Rev 5, compared to the CC1000 Development board.

2. The measured noise levels at the RX frequency of COMMA were greater compared to COMMB, indicating a possible explanation of better measured sensitivity of COMMB.

3. In some cases the crystal harmonics of CDH Rev 4 were 15-20 dB greater than the crystal

harmonics of the CC1000 development board. This is most likely caused by not following the recommended layout.

Table 29 – Conclusions from the noise measurements of the receive line

Table 29 shows conclusions derived from measuring the noise floor of CDH Rev 4, Rev 5, and the CC1000 development board. A new layout of the PolySat COMM system, using the recommended layout of the CC1000, could reduce broadband noise [16] possibly improving sensitivity.

6.1.3 Receive Line of CC1000 – Noise Floor over 70 CM Amateur Band

After observing the broadband noise, noise across the 70 CM amateur band was measured.

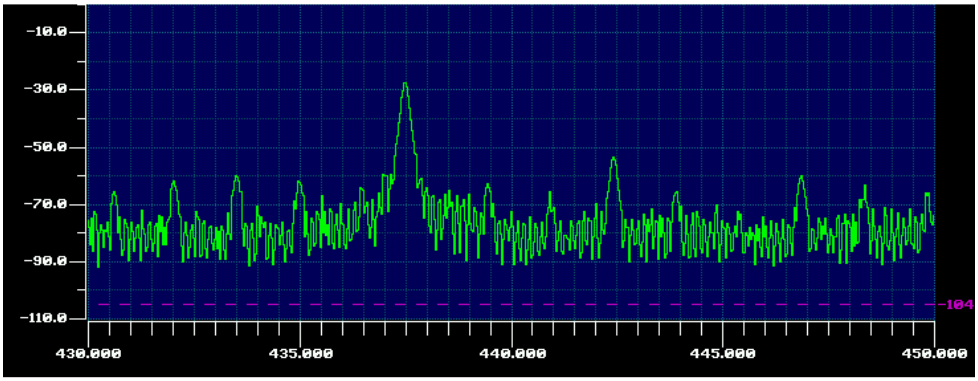


Figure 69 - CDH Rev 4, COMMA, RBW 100kHz, over the 70 CM amateur band

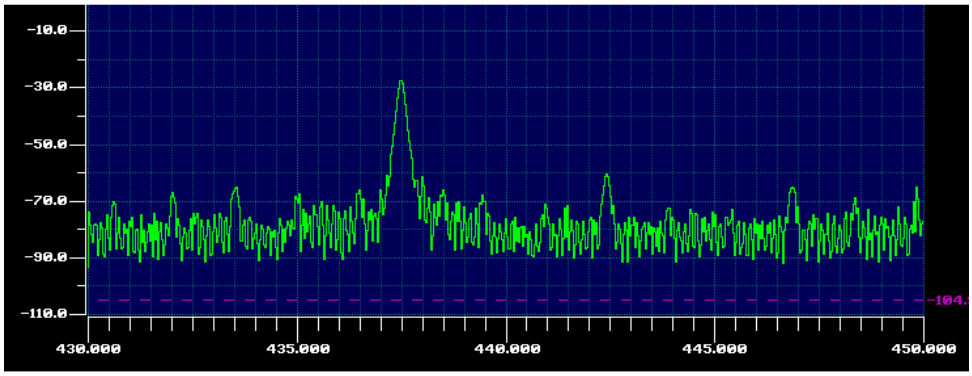


Figure 70 - CDH Rev 4, COMMB, RBW 100kHz, over the 70 CM amateur band

Only a slight difference (approximately 3dB) is noticeable between COMMA (Figure 69) and COMMB (Figure 70), but crystal harmonics are much greater (10-15dB) than the development board (Figure 71).

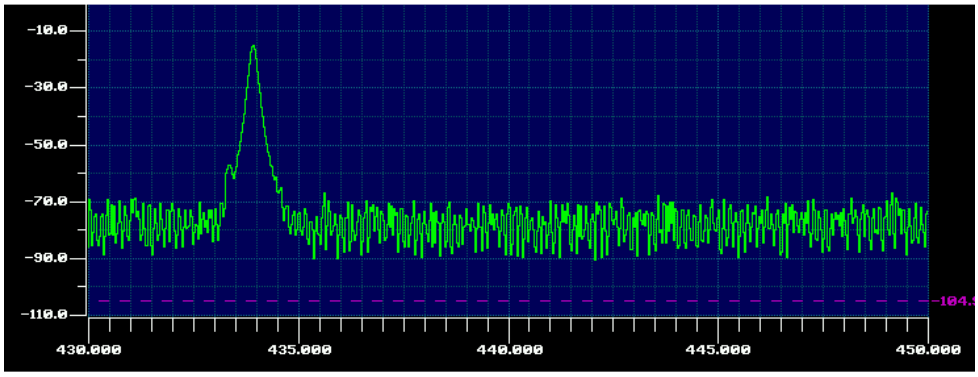


Figure 71 - CC1000 Development board, RBW 100kHz, over 70 CM amateur band

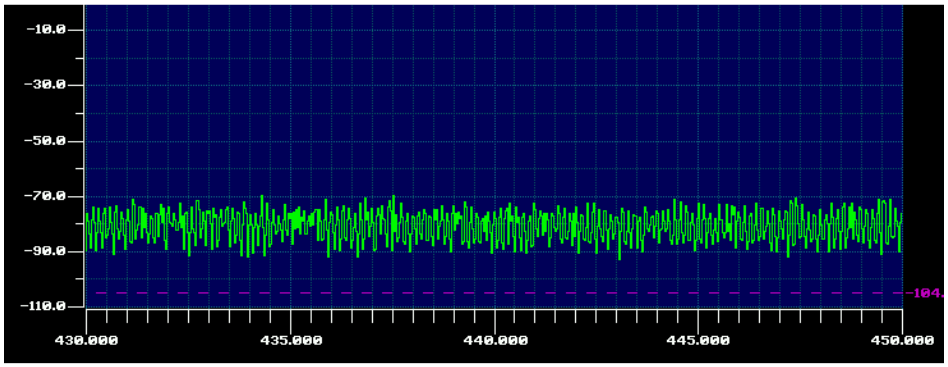


Figure 72 - System Noise Floor, over 70 CM amateur band

6.1.4 Receive Line of CC1000 – Noise Floor Characteristics

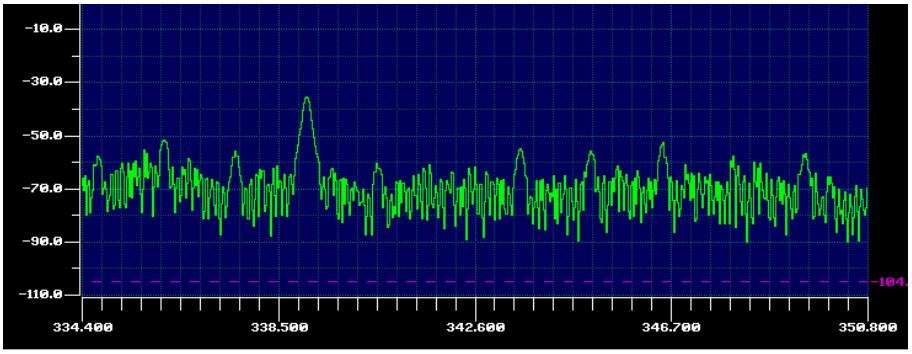


Figure 73 – The CDH Rev 4 had two types of crystal harmonics visible. The larger harmonic is spaced 14.74 MHz apart (the frequency of the CC1000 crystal) and the smaller harmonics were spaced every 1.474 MHz

Figure 73 shows crystal harmonics observed on the receive line of CDH Rev 4. The CC1000's 14.74 MHz crystal has two types of harmonics visible. The larger harmonic reoccurs every 14.74 MHz, while the smaller harmonics repeat every 1.474 MHz. Both harmonics are present from 100-500 MHz. The CC1000 development board, which uses the same crystal, shows a much more controlled and cleaner noise spectrum. By following the recommended layout, the crystal harmonics could be significantly reduced.

6.2 Testing for Reduced COMM Sensitivity from Switching Noise

After the unreliable uplink of CP3 and CP4 was noticed, several theories suggested noise on the PolySat COMM system as a possible reason for reduced sensitivity.

6.2.1 Switching Noise from DC-DC Converters

The satellite power system uses DC-DC converters to regulate the voltage from the 4.2V batteries to 3V rails used for the CDH microprocessor and COMM system. This is shown in Figure 74.

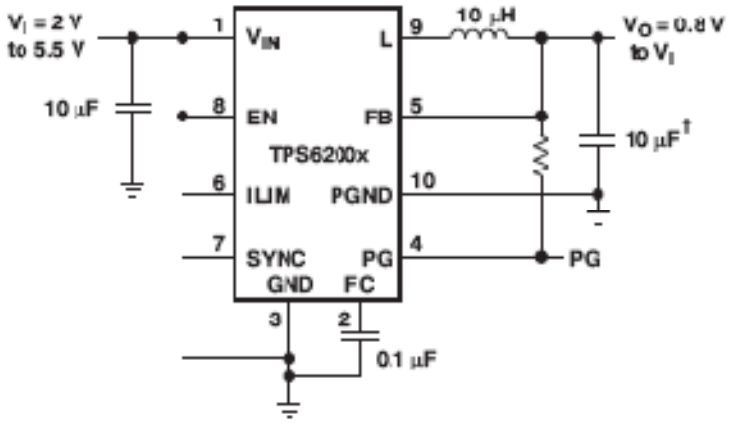


Figure 74 - The DC-DC converter regulates the battery voltage from 4.2V to 3V for the PolySat COMM System [2].

DC-DC converters typically provide a greater efficiency than linear regulators. To achieve greater efficiency, DC-DC converters switch on and off the output of the regulator at a specific duty cycle to achieve the required average output [2]. Due to this on-off switching, noise can be a significant problem. It has been thought that the harmonics caused by the DC-DC regulators are introducing noise on the bus, reducing COMM sensitivity [4]. To test for a reduction in sensitivity caused by switching noise of the DC-DC converters, the sensitivity of each CDH was measured with and without the DC-DC converters. Since the Faraday Cage has two ports for passing through DC power, each COMM (CDH Rev 4 and Rev 5) was powered from a 3V linear power supply for the CDH. The DC-DC converters were physically removed from the EPS, ensuring that the only 3V rail was from the linear power supply (without the associated noise from switching converters). The test was repeated again, this time using the DC-DC converters to power the COMM and CDH. No significant difference in sensitivity was noted (Table 30), eliminating switching noise of the DC-DC converters as a cause poor sensitivity. In retrospect, it is unlikely that the DC-DC converters would reduce sensitivity, since switching occurs at 750 kHz. The harmonics at 437 MHz are likely to be very small and the IF of the CC1000 is at 150 kHz.

		DC-DC Converters	Linear Regulator
CDH Rev 4	COMMA	-89 dBm	-88 dBm
	COMMB	-94 dBm	-93 dBm
CDH Rev 5	COMMA	-92 dBm	-94 dBm
	COMMB	-102 dBm	-101 dBm

Table 30 - Testing for differences in sensitivity caused by DC-DC converters. No significant difference in receive sensitivity is observed without the DC-DC converters, eliminating them as suspect in causing desensitization of the COMM system.

6.2.2 Switching Noise from I^{2}C Bus

The I^{2}C data bus consists of two lines, SCL and SDA. The SCL is the clock, which switches at 100kHz, suspiciously close to the CC1000's 150 kHz IF. In order to test for interference, both COMMA and COMMB were tested individually without the CDH microprocessor powered.

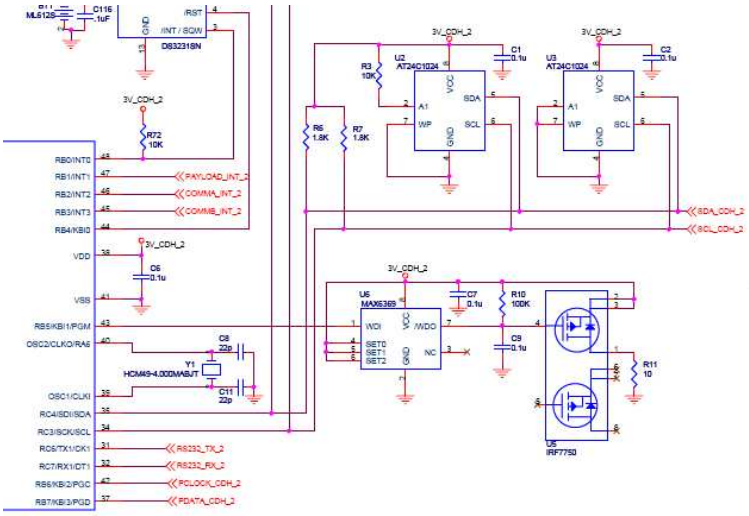


Figure 75 - I^{2}C switching (SCL_CDH_2) and data line (SDA_CDH_2) originate from the CDH processor [3].

The I^{2}C bus originates from the CDH microprocessor (Figure 75), so without it on, there is no clock or data line. Then, with the CDH microprocessor programmed and powered, the sensitivity was measured again. No difference in receive sensitivity was found, eliminating I^{2}C switching noise as a cause of reduced sensitivity. While the LNA internal to the CC1000 is broadband, it most likely would not amplify signals in the hundreds of kilohertz range. Therefore, any interference at the IF could possibly be caused by leakage into the IF from the RSSI pin. A 150 kHz square wave (1.5V$_P$, 1.5V offset) was applied to the RSSI pin of the CC1000, with the goal of intentionally introducing interference at the IF. The receive sensitivity was measured again (Section 4.11) and no reduction in sensitivity was observed. The I^{2}C is not reducing sensitivity of the COMM system.

6.3 Additional Issues Relating to Inconsistent Uplink

Several observations suggest that the satellite's non-responsive behavior is not just a sensitivity problem. Other problems could include software bugs and problems with the way the microcontroller interfaces to the transceiver.

6.3.1 Observations from CP3 and CP4

When the unreliable uplink was first diagnosed as poor sensitivity, SRI's 60 meter dish was used for uplink to CP3 and CP4. Compared to PolySat's ground station, the large dish offers a tremendous increase in gain. However, CP3 did not respond to any commands sent, suggesting that problem is more than just poor sensitivity of the COMM system. CP4 responded to a few commands, but the overall results were very surprising. It was expected that the SRI dish would have no problem closing the uplink.

6.3.2 Observations from Sensitivity Testing

Throughout the testing process (from September 2009 to February 2010), several software glitches were observed.

1. Extra or repeated responses to commands
2. "Broken record" – During a response to a command, the satellite would lock up and continue to respond indefinitely until the satellite was reset.
3. Non-stop beaconing – similar to 2, as the satellite was turned on it, it would transmit beacons continuously.
4. No response – the satellite would not respond to any commands at all.

Table 31 - A list of four common satellite behavior problems observed during sensitivity testing

Months of testing showed that TestSat would not always behave as expected. Table 31 shows a list of common behavioral malfunctions. Each of these malfunctions is caused by software bugs. The software team is aware of these problems, as they were first observed during software development. A few times during testing, TestSat stopped responding altogether. This happened relatively infrequently (approximately 10 times), but is problematic for several reasons. First, the only solution was to hard reset the satellite, which can't be done in space. There are watchdog timers for each microcontroller, but a reset only occurs if they get stuck in loop and fail to keep tapping the timer [3]. The Smart Fuses only cut power (thereby resetting the satellite) if the current limit is exceeded [2]. Second, over a 6 month period of testing CDH Rev 4 and CDH Rev 5, which is the target life span of a CubeSat, problem 4 (Table 31) occurred during sensitivity testing in the lab approximately 10 times. With CP3 and CP4 almost 3 years old now, it is highly likely that this behavior could have also occurred at least several times in orbit.

Problem 4 of Table 31 was first observed while measuring receive sensitivity (Section 4.11) of the PolySat COMM system (both CDH Rev 4 and Rev5). The satellite was sent beacon commands, while reducing the signal strength. At some point, the satellite could no longer decode the command and respond. Occasionally, the satellite would stop responding at all, even as the power was increased above the dropout threshold. Increasing the power back all the way to -50 dBm still did not prompt a response from the CDH under test. A hard reset (cycling the power of the satellite) was the only way to solve this problem. This suggests that the uplink problem may be more than just poor sensitivity. One characteristic of Problem 4 (Table 31) was that it usually occurred at (or very near) the sensitivity threshold (Figure 44).

6.3.3 Long Duration Communication Test

Testing for the problematic behavior (Table 31) was difficult because of how infrequently it happened. There was no specific pattern, so reproducing the behavior was difficult to do. In order to quantify how frequently the erratic behavior occurs, a long duration test was performed. TestSat, an exact model of CP3 in orbit used for software development, was left on for three days. It was programmed with flight code, to ensure behavior as close as possible to the satellites in orbit. Beacon commands were sent to the satellite every 60 seconds, and each response was recorded. The approximate power reaching TestSat was -50 dBm, eliminating poor sensitivity as a culprit.

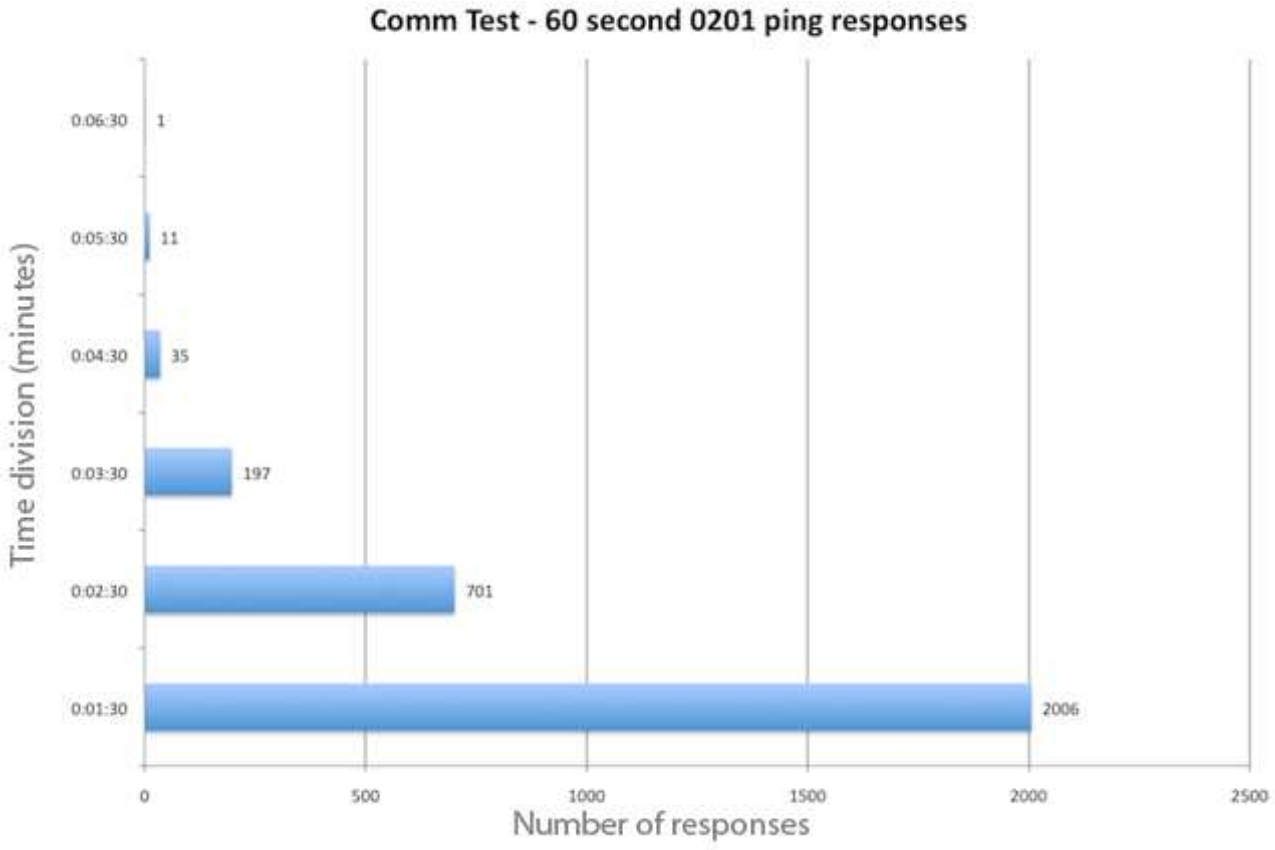


Figure 76 - Beacon commands sent every 60 seconds, and the satellite responses monitored. The horizontal axis shows how many satellite responses there were for each command from the group station. The vertical axis is divided into bins, showing that not every command received a response.

Figure 76 shows a histogram of the results of the three day communication test. The X-Axis indicates how many ACKs (acknowledgements) the satellite made in response to the beacon command, and the Y-Axis shows the time period is divided into 1.5 minute sections. The first bin (labeled 1:30 in Figure 76) shows the number of ACKs that occurred in less than 1 minute and 30 seconds. Since the beacon command was sent every 60 seconds, it is expected that the most responses occurred during the first bin. 701 responses occurred between 1:30 and 2:30, indicating that not all commands received a response. One response occurred during the 6:30 bin, showing that at some point the satellite did not respond for over five and a half minutes.

Test Duration	70 hours
Commands Sent	4199
Acknowledgements	2952
Successful Uplink	70.3%

Table 32 - Long duration COMM test results

From this test, it is clear that the satellite does not respond to every command. Even within the link margin, the uplink is only 70.3% successful. Poor sensitivity may not be the only cause of problems seen in orbit. It also offers a possible explanation of why an uplink couldn't be established with CP3 while using the SRI dish. However, this was not the exact problem observed during sensitivity testing, because Figure 76 shows the COMM recovered usually in only a few minutes. During sensitivity testing, the satellite would not recover (from the software error labeled Problem 4 in Table 31), even after waiting 20-30 minutes. Only a hard reset of the satellite would clear the error. The long duration testing occurred without the sensitivity measurement test setup (shown in Figure 12). Perhaps it is necessary to attenuate the signal to the threshold of sensitivity to recreate the error (Problem 4 in Table 31) during the long duration test. This may provide more information. It is not clear what is causing the satellite to not

respond to commands. More long duration tests could possibly reveal a pattern. Additional software testing should be performed to help troubleshoot this problem.

Chapter 7. Results of Sensitivity Testing

7.1 Comparison of COMM Sensitivity

7.1.1 Overall COMM Performance

CDH Rev 4 typically responded to packets down to around -89 to -92 dBm, while CDH Rev 5 performed significantly better, responding to commands down to -100 to -101 dBm. The LNA provided a significant increase in sensitivity. A summary of each board tested can be seen in Table 33.

Board	Sensitivity		Comments
	COMMA	COMMB	
CDH Rev 4	-89 dBm	-92 dBm	
CDH Rev 5 (#1)	-94 dBm	-101 dBm	LNA increases sensitivity
CDH Rev 5 (#2)	-96 dBm	-100 dBm	CP5 Flight Candidate

Table 33 - Overview of the performance of COMM tested for sensitivity

7.1.2 CC1000 Performance

The datasheet sensitivity for the CC1000 is -110 dBm (FSK modulation, data rate of 2.4 kBaud, with a separation frequency of 64 kHz). The wide separation frequency is a potential problem with the transceiver. For best sensitivity, the separation frequency needs to be 64 kHz, and the datasheet explicitly states this [8]. Since the AX.25 standard is used for packet communication with Audio Frequency Shift Keying (AFSK) modulation, the separation frequency actually used on the CP Bus is 2 kHz [7]. Most likely, this reduces the achievable sensitivity, but the datasheet does specifically list the expected sensitivity for a separation frequency of 2 kHz at 600 baud. With CDH Rev 5 successfully decoding packets down to -101 dBm, the CC1000 is performing reasonably well. A new layout could reduce broadband noise (see Section 6.1), possibly increasing sensitivity by several dB. Although the sensitivity of the

PolySat COMM system is ultimately determined by the CC1000, the LNA incorporated in Rev 5 is clearly capable of increasing the overall sensitivity. By following the manufacturers recommended layout of the CC1000, it could be possible to achieve several dB of sensitivity.

7.1.3 PolySat COMM Performance Compared to Future Replacement Transceiver

The Axsem AX5042 will replace the CC1000 as the transceiver for the new PolySat COMM system. According to the datasheet, the stated sensitivity is -122 dBm at 1200 baud [17].

	Datasheet Sensitivity: -111 dBm **Conditions:** FSK modulated data at 1.2 kBaud, separation frequency 64 kHz
	Datasheet Sensitivity: -122 dBm **Conditions:** FSK modulated data at 1.2 kBaud

Table 34 – Sensitivity comparison of CC1000 and the AX5042 future replacement transceiver. The datasheet of the AX5042 states that the receive sensitivity is not dependent on FSK frequency separation [17].

The listed sensitivity of the Yaesu FT-847 is -125 dBm, with a measured sensitivity of -115 dBm. If the AX5042 can perform similarly, the team should have no problem closing the uplink.

7.2 Recommendations for Improving Uplink and Future PolySat COMM

Based on the results of the testing, several recommendations can be made. These include recommendations directly applicable to CP5, the last satellite to utilize the current CP Bus, and also recommendations to aid future bus development.

7.2.1 Improved Layout of CDH Rev 5

Crystal harmonics and broadband noise (Section 6.1) on the PolySat COMM system could be reduced. While it's not clear how much the noise is reducing the sensitivity, proper layout techniques could significantly reduce noise seen at the RX line of the CC1000, possibly improving sensitivity. This is especially important with CDH Rev 5, as in some cases, the LNA of COMMA is amplifying the broadband noise at the receive line at the input of the LNA. Measured sensitivities of COMMA and COMMB differed, and differences in layout of each COMM could be causing this. Application notes for suggested layout of the CC1000 are available from Texas Instruments, and detailed information about reducing EMI is available online. With CP5 using the same PolySat COMM system, a new layout is highly recommended to maximize hardware performance.

7.2.2 COMM Software Testing

Based on the results of the long duration test, it is suggested that the COMM uplink is only approximately 70% even in favorable conditions. Software testing should be done to determine there is any way increase reliability of the COMM. Long duration testing should be performed using the test setup to reduce the signal strength close to the threshold. This will closely replicate the orbital conditions, allowing a better indication of COMM performance.

7.2.2 Temperature Controlled Crystal Oscillator

The CC1000 datasheet recommends using a very inexpensive 14.7456 MHz crystal to keep costs down. The downside is that a cheap crystal can fluctuate significantly (up to 50 parts

per million over a large temperature range). Since most SRD (Short Range Device) applications are mass produced, this is understandable because reducing cost is a high priority. Additionally, the assumption is made that both the transmitter and receiver exist in environments of similar temperatures. Since PolySat is not mass producing CubeSats, using a more expensive crystal to gain better stability over temperature is not an issue. In CubeSat applications the temperature can vary greatly, so a cheap crystal could be a problem if the transceiver's PLL (Phase Lock Loop) needs a very stable reference. From on-orbit data, the side panels of CP3 experienced temperature swings from +40 to -30 °C [4]. Application Note 0019, available from Texas Instruments, discusses problems with the receive sensitivity due to crystal frequency variation over a large temperature range [14]. The RX/TX frequencies are set by a Phase Lock Loop (PLL) set from the crystal oscillator, so any drift of the crystal will cause the receiver and transmitter center frequencies to drift.

	Crystal Inputs	
Initial tolerance, ±	30	ppm
Temperature drift, ±	50	ppm
Aging, ±	5	ppm
Load error	2	ppm
Total	87	ppm

Table 35 - Total variation of crystal over a large temperature range, calculated from application note AN019 available from Texas Instruments

Total frequency error possible for TX, ± :	**35.2**	**kHz**
Total frequency error possible for RX, ± :	**35.2**	**kHz**
Worst case IF frequency error, ± :	**70.3**	**kHz**

Table 36 - Resulting IF error, caused by temperature variations

Table 36 shows that a variation of up to 70.3 kHz of the IF is possible. The IF tracks the LO with a 150 kHz offset, and crystal frequency variations caused by temperature will While this

represents the worst case, the bandwidth of the IF is 175 kHz, and a variation of 70 kHz could shift the 150 kHz IF closer to the edges of the IF filter.

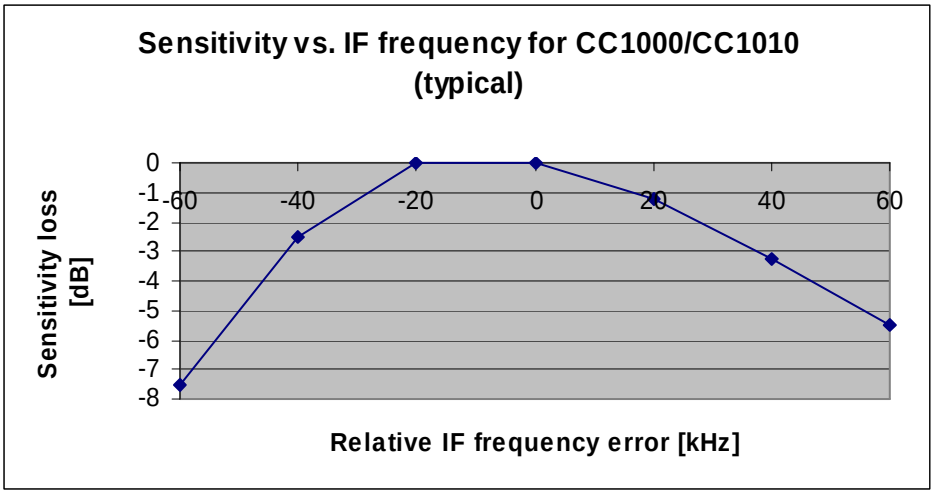


Figure 77 - Variations of the IF due to the crystal can cause a reduction in the sensitivity of the CC1000

Figure 77 shows that sensitivity loss can occur with large variations of the IF. This chart is for a frequency separation of 64 kHz, so the PolySat COMM system may see less of a reduction in sensitivity since a 2 kHz separation frequency is used. This is because the lower frequency separation will have more tolerance to frequency errors. However, it does emphasize the fact that a reduction in sensitivity could be caused by a low quality crystal. Instead of using a crystal as a reference, a Temperature Controlled Crystal Oscillator (TCXO) could be used to maintain stability over temperature. Using a TCXO could reduce crystal frequency variation to less than +/- 5 PPM, compared to the current crystal varying +/- 50 PPM. Even though a wider frequency separation is more susceptible to decreased sensitivity from crystal variation, the application note recommends against reducing the frequency separation (since maximum sensitivity is achieved with a 64 kHz separation). This is further evidence that using a 2 kHz frequency separation is possibly causing reduced sensitivity of the CC1000. After the potential problem of reduced sensitivity caused by crystal variations over temperature was discovered, a

heat gun was used to heat the CC1000 and the crystal to approximately 50°C. The LO leakage (see Figure 55), monitored with the Spectrum Analyzer, was observed to shift by 30 kHz, verifying that the cheap crystal is capable of causing a significant shift of the IF.

7.2.3 Proper Testing Procedures to Verify the RF Chain

Significant improvements can be made to the board testing procedures, especially for the RF Chain/COMM. Through RSSI characterization of the CC1000, a manufacturing defect was found in a board that was labeled as "fully functional." After each hand-soldered board is completed, student developed testing procedures are used to check each subsystem. After each subsystem is tested, the board is programmed with code, and the COMM system is tested. After the CDH Rev 5 was completed, the testing procedures were not updated, resulting in out-of-date procedures. The outdated procedures were skipped, and in this case a serious manufacturing defect was not detected. A board's COMM system is deemed working if it can respond to a beacon command. However, even with 30 dB of attenuation on the radio, the output power is high enough to trigger the response from the CC1000, just through spurious emissions from the transmitter inducing RF currents through the PCB traces.

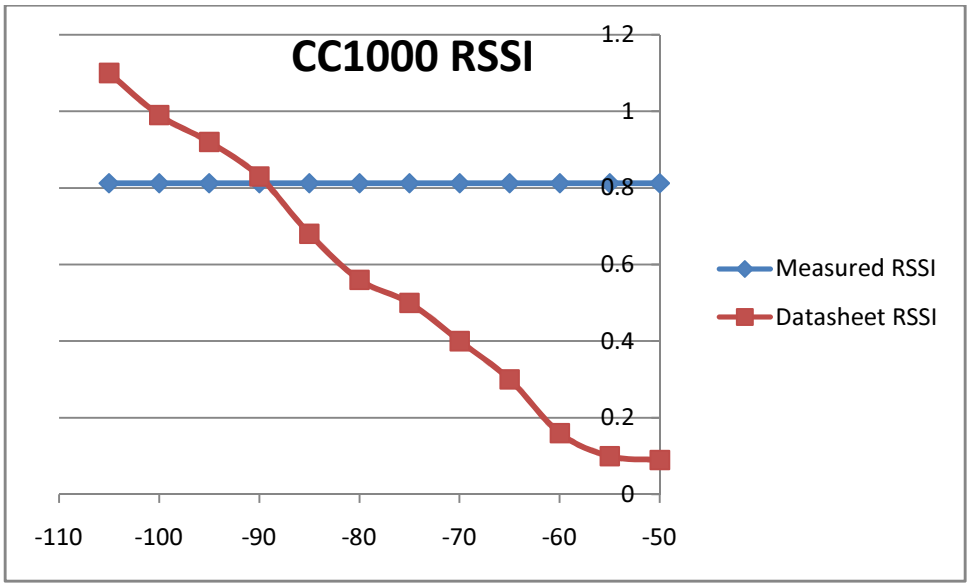


Figure 78 - RF Chain testing of CDH Rev 5. Using the RF source, a signal at 437 MHz was applied to the antenna connector. The CC1000 is not receiving any signal through the antenna connector, indicating a manufacturing defect in the RF chain.

Based on these testing procedures, the CDH Rev 5 characterized in this thesis was qualified as a "fully functional board." However, once placed in the Faraday Cage for sensitivity characterization, a significant problem was observed: none of the RF power reaching the transceiver was going through the U.FL connector. The test setup's high degree of isolation (see Figure 12) ensured that the signal was reaching the CC1000 only through the RF chain, allowing a much more accurate assessment of COMM functionality. Systematic testing narrowed the problem down to a specific manufacturing defect: the LNA of COMMA was not receiving power, causing an attenuation of over 40 dB. Since past testing procedures qualified a partially functioning board as a flight candidate, an updated qualifying procedure is needed, including a direct measurement of the receive sensitivity using the setup in Figure 12.

7.2.5 U.FL Connector Problems

The U.FL female connector (Figure 80), which mates with the on-board antenna connector of the RF Chain (see Figure 49 and Figure 50), has a tendency to fail as an open circuit. With an open circuit failure, any RF power will be completely reflected back to the source. An open circuit failure of the U.FL connector would essentially disconnect the antenna from the RF chain, rendering the COMM system useless.

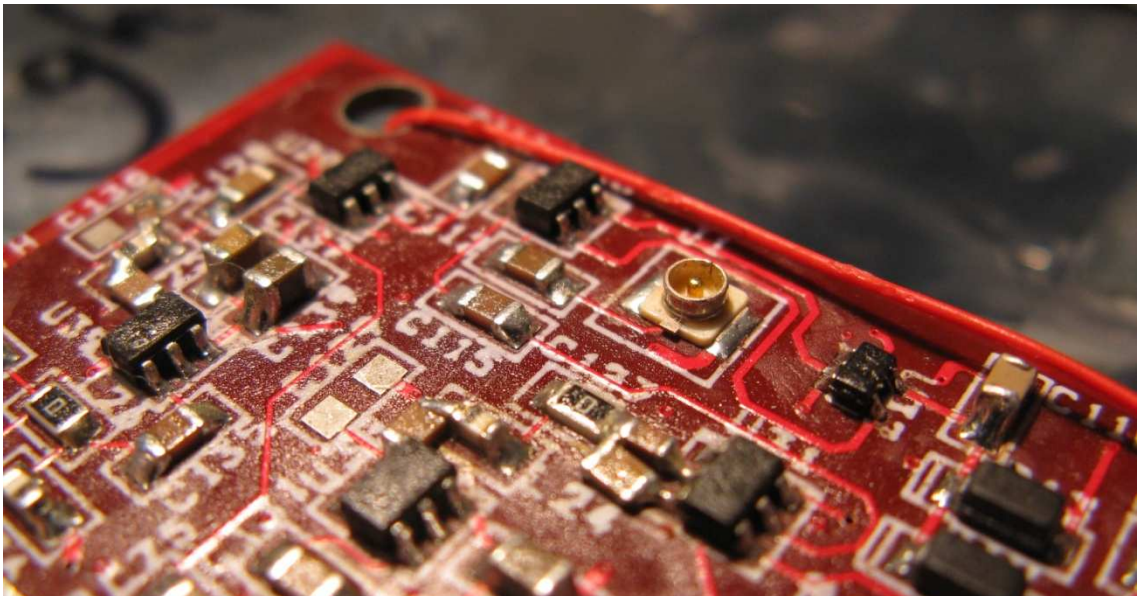


Figure 79 - Male U.FL connector on CDH Rev 5

Figure 80 - U.FL female connector with open circtuit defect (center conductor prongs are spaced too far apart) shown on left, new U.FL connector shown on right. The connector on right shows the proper center pin spacing.

The soft plastic separating the ground and signal gives way after too much use, allowing separation of the prongs (Figure 80). Since the female connector will still mate to the surface mount male connector even with an open circuit failure, it is impossible to visually detect the problem.

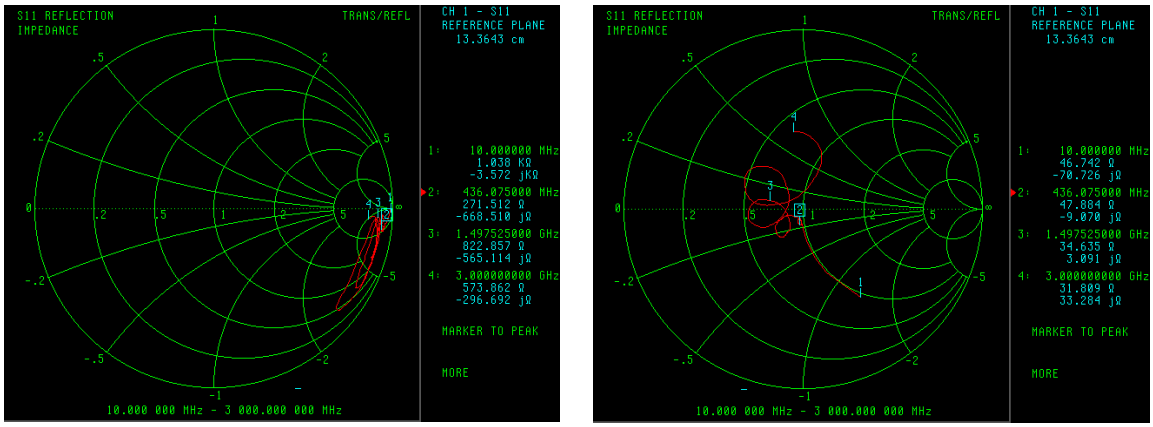


Figure 81 – A worn-out U.FL connector, on left, behaves an open circuit. By adjusting the spacing of the two prongs, a proper connection was established, shown on right.

Using the network analyzer to view the reflection coefficient S_{11}, it is shown that a faulty U.FL connector behaves as an open circuit (Figure 81). Slightly bending the two prongs back to the original spacing ensures a proper connection, evident by a reflection coefficient at the center of the Smith Chart. The U.FL connector, an RF connector with a 50Ω characteristic impedance, is a "one-time" connector. It is not meant to be repeatedly connected and disconnected, as it is rated for a maximum of 30 connections [18]. After a failure of one of the connectors was noted, all the connectors currently used in lab were checked, and almost every connector had significant damage. The open circuit failure is caused by disconnecting and reconnecting past the manufacturer's specified maximum, and also by applying too much force while connecting or disconnecting. A special tool is available for correctly connecting the connector. A simple way to verify the U.FL connector is behaving correctly is to perform a continuity check with a multi-meter. A visual inspection of the connector should also be performed (see Figure 80).

1. Visual inspection of female U.FL connector (See Figure 80)
2. Limiting the number of connections made
3. Use proper tool to mate male and female U.FL connectors
4. Continuity check with multi-meter

Table 37 - A list of possible ways to mitigate open circuit failure of the female U.FL connector

Although past testing procedures may not have detected this, testing each finished board using the receive sensitivity test setup (Figure 12) could easily identify a problem in the RF chain. The U.FL connector's small size makes it desirable to use in CubeSat applications. The desirable features warrant continued use, as long as precautions are taken to prevent failures.

7.2.4 Contract Manufacturing of Assembled boards

Each CDH board is soldered by students in the PolySat lab. This is a several step process. First, the necessary parts are gathered, a process called “kitting.” Then, each component is hand-soldered using a fine tip soldering iron and a microscope, called population. Finally, the board is tested to make sure it works. There are several drawbacks to this approach, the biggest of which is reliability. It can be very easy to make errors during component population of the board, such as using the wrong capacitor. Troubleshooting a non-working CDH board is also very difficult. As discovered through sensitivity testing, the current testing procedures aren’t capable of identifying all possible problems. Fully assembling and testing a CDH board requires significant resources, tying up students with a rather mundane task. With PolySat’s limited student resources, this is not the best use of their time. Software and hardware development is also hindered. Because the process of assembling a CDH is resource intensive, it seems the lab is always experiencing a shortage of hardware. A solution to improving reliability and conserving student resources is to have the boards assembled by a company specializing in PCB assembly. The drawback is added expense, but the increase in reliability and resources saved would offset this expense. With professionally assembled boards in lab, both hardware and software development would be less hindered by hardware shortages and reliability issues.

7.2.6 High Frequency Probe

To facilitate COMM system development, the lab should be equipped with a high frequency probe. Similar to a scope probe, this would allow troubleshooting at RF frequencies. Several of the difficulties encountered during this thesis could have been avoided with a high frequency scope probe. The HP 85024 High Frequency Probe, capable of measuring signals from 300kHz to 3GHz, is the preferred solution. It is directly compatible with the Spectrum Analyzer

in lab, except it does require the separate power supply. The probe features high sensitivity and a very low shunt capacitance, which means it won't load down the circuit being measured at higher frequencies. Verification of the RF chain could be easily accomplished by applying an RF source at the antenna connector, and probing at different points. A used probe can be bought off of eBay for around $1,200.

Chapter 8. Summary

8.1 Receive Sensitivity Test Setup

8.1.1 Sensitivity Characterizations

The test setup developed to measure receive sensitivity (Figure 12) worked very well. It is considered successful for several reasons. First, the setup is capable of making accurate and consistent sensitivity measurements. Second, the setup was used to characterize the COMM system of the CP Bus, which was incompletely tested on earlier satellites. The data collected provided valuable information to assess the capability of the COMM system. Finally, the test setup is versatile, capable of being utilized in future receiver development. It can also act as a tool for selecting the most sensitive board among flight candidates.

8.2 CDH Sensitivity Performance

8.2.1 CDH Rev 4 versus Rev5

The addition of the LNA on CDH Rev 5 successfully increased the sensitivity of the CP Bus. Compared to the link budget, however, the sensitivity of the CP Bus is still not enough. A more sensitive transceiver is needed.

COMM	Sensitivity	Comments
CDH Rev 4	-90 dBm	CP3, CP4
CDH Rev 5	-100 dBm	Includes LNA, CP6
Yaesu FT-847	-115 dBm	Ground Station

Table 38 - Measured receive sensitivities of CDH Rev 4, Rev 5, and the PolySat ground station receiver

8.2.2 Noise Characterization of the Receive Line

The noise analysis in Section 6.1.1-6.1.4 shows significant differences in the noise floor of CDH Rev 5. Of the two CDH Rev 5 boards measured for receive sensitivity (Section 4.11), there was a significant difference in sensitivity between each redundant COMM. For both boards, broadband noise polluted the receive lines in front of the LNA on COMMA. Reducing broadband noise can be achieved by placing a narrowband filter in front of the LNA, and following proper layout guidelines.

8.2.3 Link Budget Compared to Receive Sensitivity of CDH Rev 5.

For both revisions of the PolySat COMM system, the sensitivity does not provide enough link margin (see Section 3.2.3 and 3.2.4). While the sensitivity of the PolySat COMM system is ultimately limited by the CC1000, a revision of the board could increase sensitivity, and additional software testing and modifications could help improve consistency.

8.3 CC1000

8.3.1 Limitations of the CC1000

AX.25, an amateur radio packet communication standard, was chosen as the communication protocol. Bit rates, typically 1200 bits/s, usually do not exceed 9600 bits/s, and transmission occurs using Audio Frequency Shift Keying (AFSK). AFSK utilizes a carrier modulated 1200 Hz and 2200 Hz audio tones, corresponding to 0’s and 1’s. The spacing between the two frequencies denoting 0’s and 1’s is called the separation frequency.

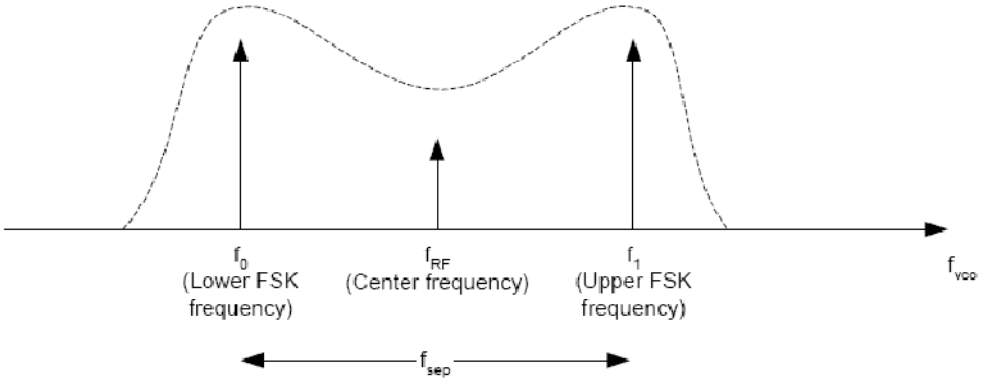


Figure 82 - Frequency separation

The CC1000 was not originally designed to receive and transmit 1200 baud AX.25 packets at amateur frequencies using AFSK [7]. Because the CC1000 is a single chip transceiver, only digital information can be passed to the transceiver on the DIO line. Then, the CC1000 outputs a modulated RF signal. Since the CC1000 is not designed for AFSK, for a successful downlink, a translation must be made from FSK to AFSK. This is done by using LSB (lower side band) mode of the Yaesu FT-847, which only demodulates half the FSK signal. The FSK tones from the CC1000 correspond closely to the 1200/2200 Hz tones of the AX.25 AFSK standard, allowing packets to be decoded by MixW software. As mentioned before, a major limitation of the CC1000 is the data rate dependency on separation frequency. In order to properly receive a packet, the frequency separation must be at least twice the bit rate. For a 1200 baud uplink, a minimum separation of 3 kHz is required. However, the bandwidth of the Yaesu's SSB (single side band) filter is 400 Hz to 2.2 kHz (at -6 dB), harshly limiting the FSK separation frequency of the uplink. As a compromise, the uplink data rate was reduced to 600 bits/s, and the separation slightly increased to 2 kHz. Luckily, the Yaesu transceiver does not have a data rate limitation based on separation frequency, allowing 1200 bits/s at a spacing of 2 kHz.

8.3.2 Overall Sensitivity

A separation frequency of 64 kHz is recommended for the CC1000. The PolySat COMM system, utilizing AFSK rather than true FSK, has a separation of 2 kHz. Although the datasheet doesn't list receive sensitivity information for a setup of 0.6 kBaud at a separation of 2 kHz, a comparable ratio is 4.8 kBaud at 20 kHz. The listed sensitivity is -104 dBm for NRZ encoding. With CDH Rev 5 responding to packets down to -100 dBm, the CC1000 is, for the most part, performing as expected. Noise could be reduced through a new layout, but the sensitivity of the bus is ultimately limited by the CC1000. To further increase the link budget, future bus designs will need to utilize transceivers of greater sensitivity. The AX5042 transceiver, chosen as the replacement transceiver for the new bus, has a stated sensitivity of -122 dBm at 1200 baud. Compared to the CC1000, this is a huge performance increase of approximately 20 dB. Most importantly, though, is the fact that the AX5042's sensitivity is not dependent on the FSK separation frequency [17].

8.4 Future Work

8.4.1 New Layout for CP5

As discovered during the noise characterization, poor layout has resulted in a large increase in broadband noise. By removing the redundant COMM, the board layout will be simplified greatly. With more board space, the CDH digital circuitry can be placed on the backside of the board, providing room for very careful layout of the RF circuitry on the top side of the board. Removing the redundant COMM would also simplify the software. Application notes and recommended layouts of the CC1000 are available from the manufacturer.

8.4.2 Receive Sensitivity versus Temperature

The recommended crystal for the CC1000 varies tremendously over large temperature ranges. With such a narrow bandwidth, any deviation from the TX/RX frequency could possible cause problems closing the uplink. Although frequency shift due to Doppler is accounted for, frequency shift caused by extreme temperature is not. All the receiver sensitivity testing done was performed at room temperature. A detailed analysis could provide valuable insight to whether this could be a problem. Instead of using a crystal, a Temperature Controlled Crystal Oscillators (TCXOs) would provide a more stable reference. This is recommended for future bus development and could eliminate problems caused by shifting receive and transmit frequencies.

8.4.3 Antenna Characterization and Re-design

The receive sensitivity determined with the test setup relies on a direct connection to the U.FL RF Connector on the satellite. This doesn't take into account the antenna gain or loss, so a detailed analysis of the antenna system would improve link budget accuracy. Since the CubeSat's small size prevents using the proper length ¼ λ dipole, the antenna is slightly shorter than it should be. It is unknown how much this is affecting the link budget. In order to increase the antenna length, the deployment system would need to be redesigned and tested. With the link budget so small, a characterization of the antenna system could help identify whether or not the antenna is a weak link in the COMM system.

8.4.4 Long Duration Testing

Long duration testing can reveal problems previously unnoticed. More testing could help identify software bugs and provide more information about the inconsistent uplink of the CP

Bus. During development of the new bus, long duration testing of the COMM system can provide very useful information on how reliable the uplink is.

8.4.5 Upgrading the Ground Station to Improve Uplink to the Satellite

The 100W amplifier could be replaced with a more powerful amplifier. The HLV-1100, a 1000W amplifier made specifically for the 70 CM amateur band, would provide an additional 10 dB of uplink margin. This is a very practical way of increasing the uplink margin, but expensive. The HLV-1100 is a built-to-order amplifier, and costs approximately $6,000.

Figure 83 - HVL-1100 1000W amplifier

AAUSAT-II, a Danish student satellite launched April 2008, also noticed a lower uplink margin than originally expected. By adding the HLV-1100, they were able to increase the uplink margin, and as of October 2008, uplink and downlink occurred on a daily basis [11]. A very useful project would be to collaborate with Aalborg University see if PolySat could use their ground station remotely. This would allow PolySat to “test-drive” the amplifier before committing to the large expense. However, with PolySat projects becoming more and more ambitious, the cost of the new amplifier is justified by an instant link margin gain of 10 dB.

8.5 Summary

8.5.1 Conclusion

Throughout the duration of this thesis, an accurate method of testing receive sensitivity was developed and documented. This was a significant development to the testing capabilities of the PolySat lab. COMM systems can be tested for receive sensitivity, noise analysis performed, and verification of the RF chain can be confirmed as a result of this test system development. Testing can occur alongside development for system verification, identifying sensitivity problems early in the development stage. CubeSat developers can easily replicate the test setup for sensitivity testing purposes, helping advance the entire CubeSat community. Using the test setup, two revisions of Cal Poly's bus, were thoroughly tested. Based on the results of this testing, it was determined that the CP Bus would greatly benefit from a more sensitive transceiver.

8.5.2 Final Words

At the beginning of this project, a solution to the poor uplink problems of CP3/4 was sought. Several unanticipated problems were uncovered, and huge developments were made in sensitivity testing. The test results show that our current receiver design still produces a marginal uplink solution. Evidence shows that the unreliable uplink is a combination of hardware limitations and problematic software. By using the testing done in this project as a template for developmental testing of a new bus, progress can be made while learning from the past. The sensitivity study performed in this thesis comes at the beginning of development of the new COMM system, providing a method to verify that the new system will have greater sensitivity.

Regardless of what the future holds, PolySat has made amazing progress in the development of CubeSats, and will continue innovation by learning from the past.

Chapter 9. Works Cited

[1] National Instruments. *1 dB Gain Compression Measurement (P1dB)*. (2009, November 30th). Retrieved from http://zone.ni.com/devzone/cda/tut/p/id/2952

[2] Day, Chris. “The Design of an Efficient, Elegant, and Cubic Pico-Satellite Electronics System.” Cal Poly Masters Thesis. December 2004.

[3] Huera, Derek. “Development of a Highly Integrated Communication System for use in Low Power Space Applications.” Cal Poly Masters Thesis. April 2006.

[4] Klofas, Bryan. “Improving Receive Sensitivity of the CPX Bus.” Cal Poly Senior Project. June 2008.

[5] Arakaki, Dean. “Experiment 4: Noise Figure and 1dB Compression Point of an Amplifer Using the Vector Network Analyzer.” EE480 Lab Manual. Cal Poly Electrical Engineering Department.

[6] PolySat. *Groundstation Equipment*. (2006, May 26th). Retrieved from http://polysat.calpoly.edu/earthstation/equipment/index.php

[7] Noe, Chris. “Design and Implementation of the Communications Subsystem for the Cal Poly CP2 CubeSat Project.” Cal Poly Senior Project. June 2004.

[8] CC1000 Data Sheet. Available at http://www.ti.com

[9] ZFRSC-42+ Power Splitter Data Sheet. Available at http://www.minicircuits.com/pdfs/ZFRSC-42+.pdf

[10] JFW MODEL 50DR-001 Data Sheet. Available at http://www. jfwindustries.com

[11] Jens Dalsgaard Nielsen and Jesper A Larsen. “AAUSAT-II, a Danish Student Satellite.” October 2008.

[12] Abel, John. “Evaluation of Particle Dampers in a Microgravity Environment” June 2009.

[13] Lim, Tiffany. “Antenna Characteristics of the CubeSat Dipole Antenna.” Cal Poly Senior Project. July 2007.

[14] “Application Note AN019: Crystal oscillator issues for CC1000.” Available at http://focus.ti.com/lit/an/swra072/swra072.pdf

[15] Kobeissi, Imad. “Noise Reduction Techniques for Microcontroller-Based Systems.” Application Note 1705.

[16] “User Manual: CC1000DK Development Kit.” Application Note. Available from http://www.ti.com.

[17] “AXSEM AX5042 Data sheet.” Data sheet. Available from http://www.axsem.com.

[18] “Ultra Small Surface Mount Coaxial Connectors – U.FL Series” Data sheet. Available from http://www.hirose.com.

[19] PolySat. *Projects*. (2009). Retrieved from http://polysat.calpoly.edu/earthstation/equipment/index.php

[20] “Drop-In Monolithic Amplifier: ERA 3+.” Data sheet. Available from http://www.minicircuits.com/pdfs/ERA-3+.pdf

[21] User Manual. “Yaesu FT-847 Transceiver.” Available from http://www.yaesu.com.

[22] Anritsu Application Note. “Noise Figure: Scorpion Option 4.” April 2000.

[23] McCabe, Keith. “Enhancements to the CPX I2C Bus.” Cal Poly Senior Project. December 2007.

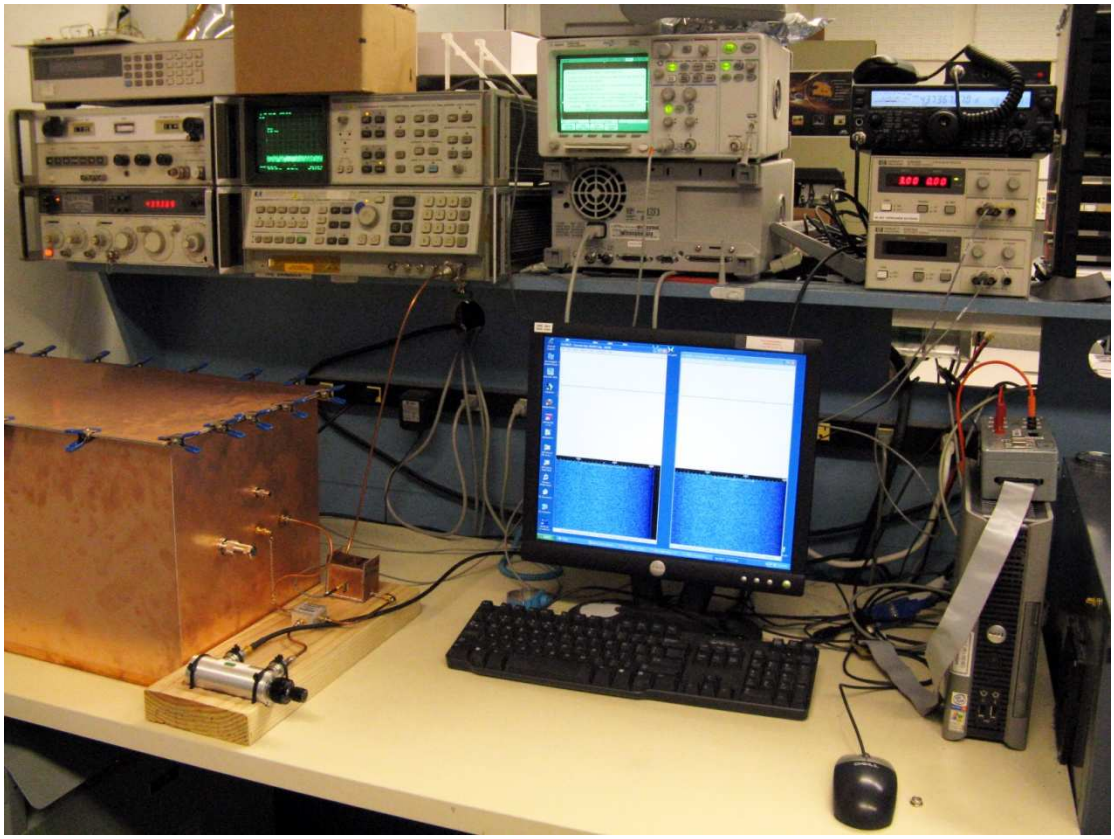
Appendices

Appendix A: Sensitivity Measurement Procedure

Ground station Installation

Setup

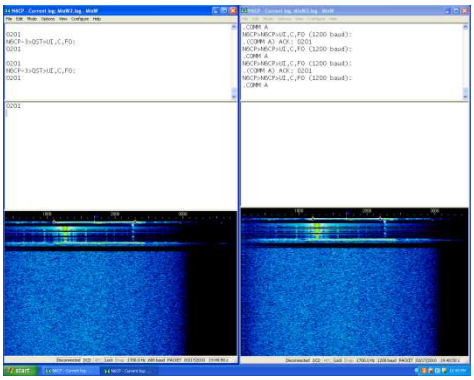
1. Gather required equipment: Faraday Cage, Attenuation Block, and the box of connectors. All of this is located in the gray cabinet listed “RF Testing.”



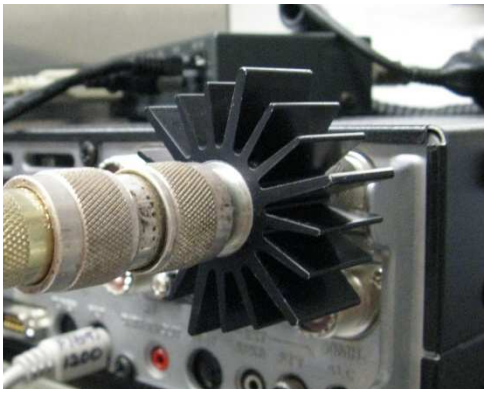
2. Double check MacDoppler on Marconi to ensure there isn’t a pass coming up for at least an hour.

3. Turn on the Spectrum Analyzer. It takes several minutes to warm up, and is not ready to display signals until a distinct “click” is heard. **WARNING: +30dBm (1W) MAX AT THE INPUT OF THE SPECTRUM ANALYZER. DO NOT EXCEED THIS.**

4. The computer at the RF bench should have MixW shortcuts on the desktop, and is already setup with the FT-847 transceiver. Turn the transceiver on.



5. Verify there is a 30dB attenuator at the 433MHz port of the Yaesu FT-847, and attach it to the input of the Spectrum Analyzer. Verify the RF Power is turned all the down (CCW).



6. Using the Center Frequency and Frequency Span buttons, set the Spectrum Analyzer to a center frequency of 437.365MHz and a span of 5MHz.
7. Measuring the output power of the FT-847: Connect the output of the radio (with 30 dB attenuator) to the input of the spectrum analyzer. Send a beacon command (0201 in MixW) and observed the magnitude on the Spectrum Analyzer. Use the marker peak search button to measure the power. It should either be around 0 to -2 dBm or -19 to -20dBm. Note which one it is, as this dictates what attenuation settings to use. **The table below shows the attenuation setting and the approximate signal strength reaching the receiver under test**.

FT-847 Output: 0 dBm	
Attenuator Setting	Power dBm
79	-105
73	-100
69	-95

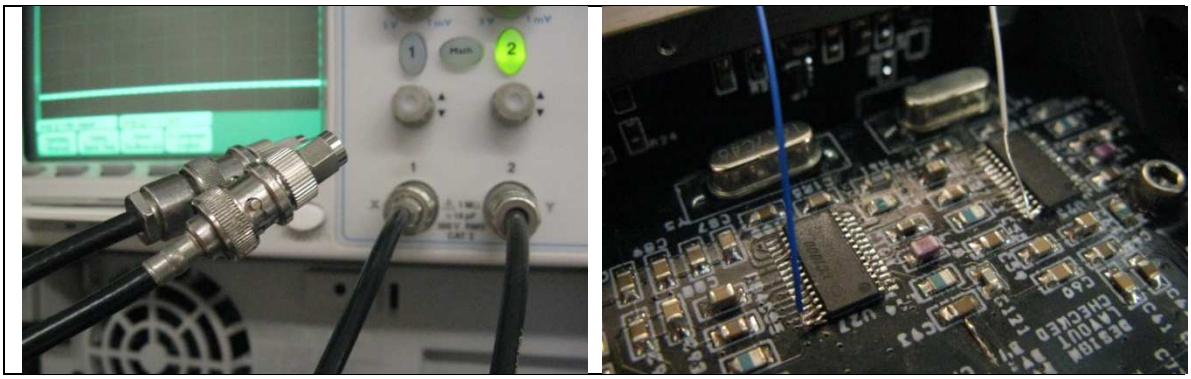
FT-847 Output: -20 dBm	
Attenuator Setting	Power (dBm)
99	-105
93	-100
89	-95

64	-90
59	-85
54	-80
49	-75
44	-70
39	-65
34	-60
29	-55
24	-50

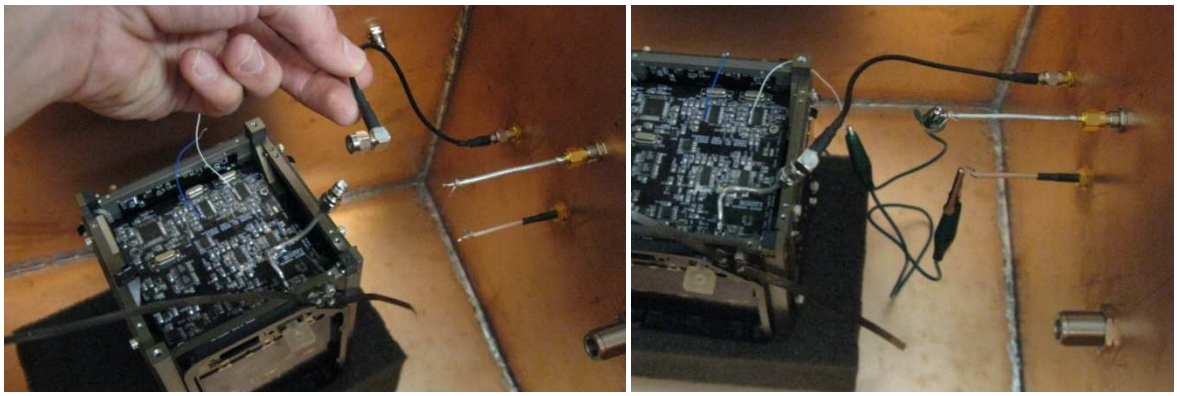
84	-90
79	-85
74	-80
69	-75
64	-70
59	-65
54	-60
49	-55
44	-50

8. Connect Port 1 of the Power Splitter to an SMA Port of the Faraday Cage using semi-rigid coax. Make sure Port 2 is terminated with a 50Ω termination (gold cap with chain).

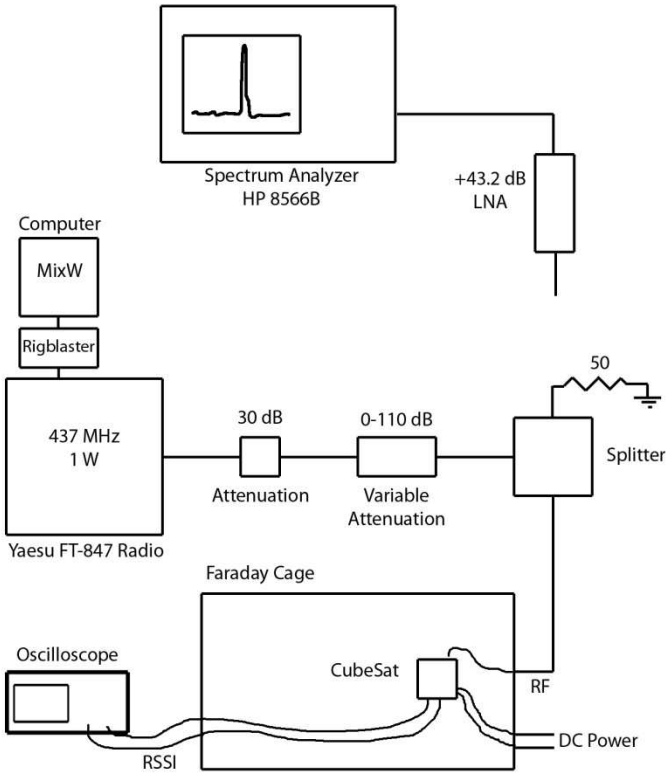
9. Connect two BNC Cables to the Oscilloscope, add SMA-BNC adapters and hook them up to two SMA ports on the Faraday Cage. From inside the cage, use alligator clips to connect to pin 28 of the CC1000. Hook up COMMA to Ch1, and COMMB to Ch2.



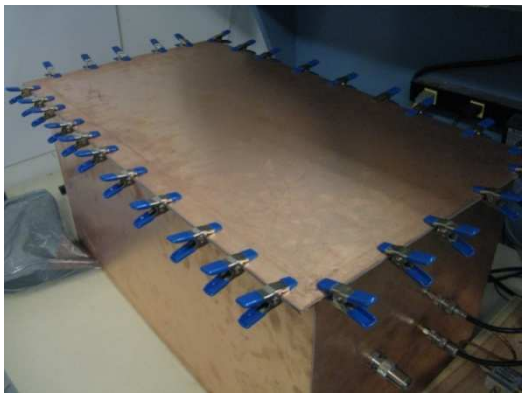
10. Using a small SMA cable (or U.FL pigtail) connect the CDH antenna jack to the SMA bulkhead for Port 1 of the Power Splitter. IMPORTANT: If using the U.FL pigtail, ensure that it actually connects to the antenna jack. Continuity check the inner conductor (signal conductor) to make sure there is a connection.



11. The test setup is complete. Verify everything is connected. It should look like the figure below.



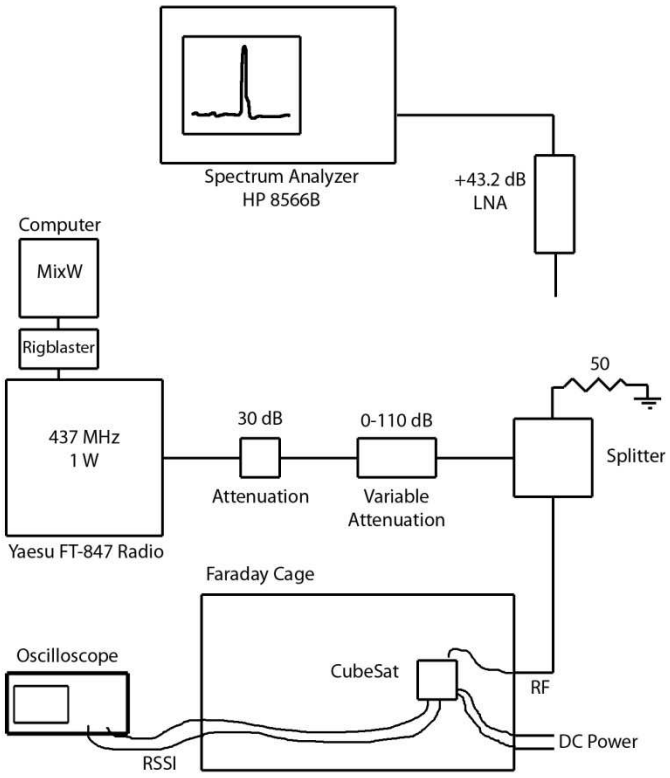
12. Remove the RBF pin. Set the variable attenuator to 24. Send the satellite a beacon command “0201” and verify that the satellite responds. This is to make sure the setup is working before you close the lid.
13. Place the lid on top of the box, and clamp it down. Make sure all unused ports are terminated.



14. Send “473c” to set the CDH in normal ops. Verify that it ACKs. Send “4800” to disable the beacon. Finally, send “410005” to set it to COMMA for approximately 30 minutes. Make sure the radio is tuned to COMMA.

Testing

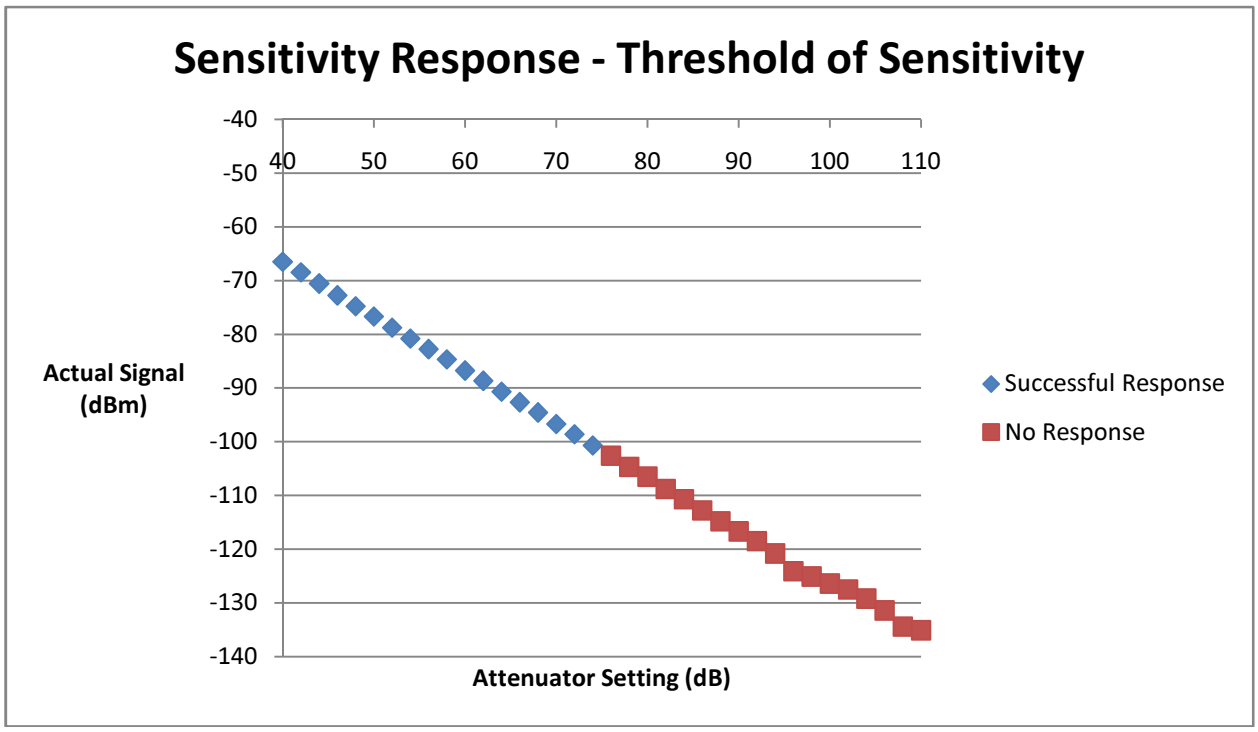
15. Open up the original Sensitivity_Test excel spreadsheet, and save it to the directory as a new spreadsheet, name it with the correct date and board revision (Eg “2010-03-02_CDH-REV4_SensitivityTest”)
16. Verify the sensitivity test setup is connected properly



Sensitivity setup for finding the threshold of sensitivity of the PolySat COMM system. The LNA is disconnected from the power splitter because the satellite response exceeds the maximum input power of the LNA and would cause permanent damage.

17. Record the resting RSSI value of COMMA using the oscilloscope (hit “quick meas” for the average of Ch1).
18. If the Yaesu FT-847 is outputting around 0 dBm of power, start with the attenuation at 44dB. Otherwise, if the radio output -20 dBm, start at 24dB.
19. Send “0201” at each of the 12 attenuation settings, and record the RSSI values. Make sure to measure the RSSI during the command, since the CC1000 monitors the RSSI in real-time. Also note at which setting the satellite stops responding.

20. Adjust the attenuation to the previous setting before the satellite stopped responding. Now, increasing the attenuation in 1dB increments, send “0201” commands until the satellite stops responding. Make sure that you stop at an attenuation which the satellite CONSISTENTLY responds. This is the threshold of sensitivity.

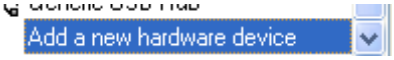


The last successfully decoded command (indicated by satellite response) is the sensitivity threshold. Once this point is located, measure the power of this signal using the LNA/Spectrum Analyzer and resending the command.

21. Attach the output of the 42.3dB LNA output to the input of the Spectrum analyzer. Using the BNC to SMB cable, bias the LNA with 11V (set a current limit of 100 mA).
22. With the attenuation set to the threshold of sensitivity (see step 20) send the "0201" command and press "Single" to freeze the display. Use the peak search to measure the value. Repeat this 5 times, recording each value. The excel sheet should subtract off the LNA gain and average the value. This value is the approximate receive sensitivity of the receiver under test.
23. Record this value in the Trial 1 box. Make sure to comment the file with all pertinent information (date, CDH version, any anomalies that occur, etc).
24. Flight candidates should be tested 3 different trials for consistency. Be sure to cycle the power so that the satellite gets a hard reset between each test.
25. Commit the file to XSERV, and put all the RF testing hardware away.

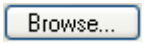
Groundstation Software Install

1. Install MixW 2.18, then copy and paste the three MixW folders into Program Files (say yes to overwrite).
2. Install the KeySpan USB-serial driver.
3. Copy the CommEmulDrv3.zip to the desktop. Extract it.
4. Start -> Control Panel -> Add/Remove Hardware. This will launch the Hardware Wizard.
5. Click Next, then click on

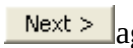
and click next again.
6. Click 

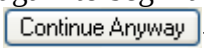
and click next.
7. Select

and click next.
8. Click on

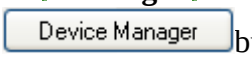
and click 

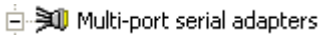
9. Select ComEmulDrv.inf from the folder you extracted it into.
10. Click

at the next screen where "MixW serial port bridge" is selected, and click 

again to begin the installation progress.
11. Click on 

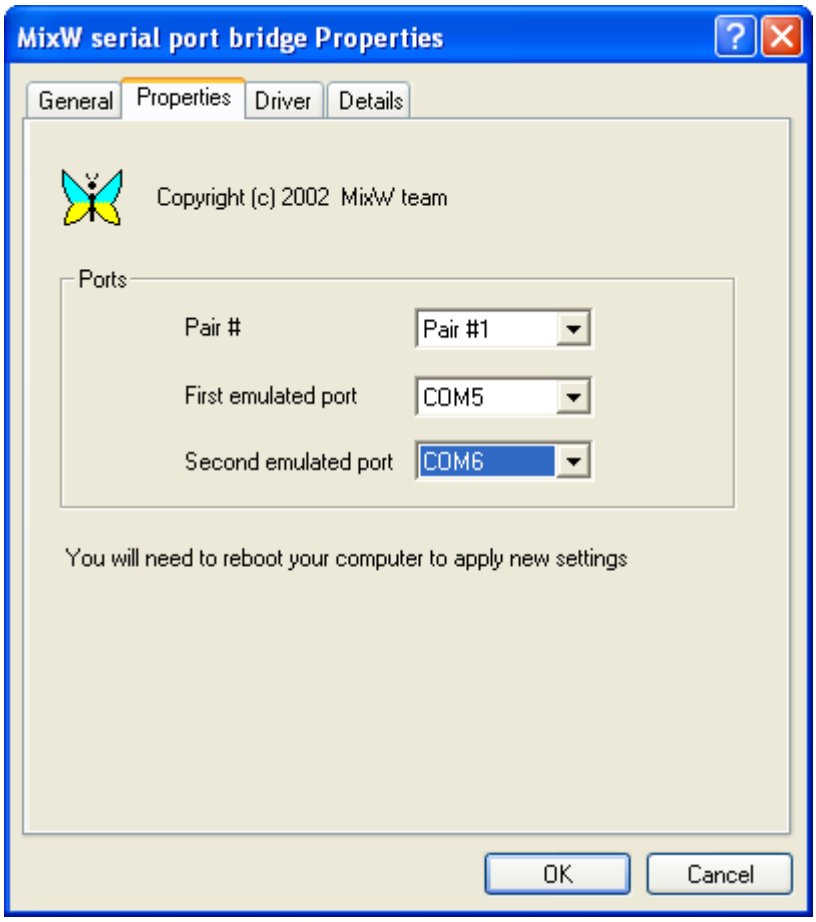
when Windows complains about the MixW serial port bridge not passing the Windows Logo testing.
12. Click

13. Save files for future reinstall.
14. Open **Start** ➡**Settings** ➡**Control Panel** ➡**System** , and click on the **Hardware** tab.
15. Click the 

button.
16. Expand 

and double-click on

. This will bring up the MixW serial port bridge Properties.
17. Select the **Properties** tab.
18. You will be presented with the MixW Serial Port Bridge Properties. Set Pair #1 to COM5 and COM6. Set Pair #2 to COM7 and COM8



19. Reboot the computer.
20. Add Uplink and Downlink shortcuts for easy access.

Appendix B: List of Acronyms

AFSK – Audio Frequency Shift Keying
ATL – Advanced Technologies Laboratory
CDH – C&DH, Computer and Data Handling
COMM – Communications system
COTS – Consumer Off the Shelf Components
CP Bus – Cal Poly Bus, standardized bus developed for CP2, revised for CP3 and CP6.
DANL – Displayed Average Noise Level
dB – Decibel
dBi – Decibel referenced to an isotropic antenna
dBd – Decibel referenced to a dipole antenna
dBm – Decibel referenced to 1 mW of power
DESENS – Desensitization
DUT – Device Under Test
EMC – Electromagnetic Compatibility
EPS – Electrical Power System
FR4 – Woven fiber glass with resin, principle component of circuit board
FSK – Frequency Shift Keying
GHz – 10^9 Hz
I^2C – Inter-Integrated Circuit, a low-speed two wire bus developed by Philips
IF – Intermediate Frequency
ISM – Industrial, Scientific, and Medical
LNA – Low Noise Amplifier
MHz – 10^6 Hz
NPS – Naval Postgraduate School
PIC – Programmable Interface Controller
PCB – Printed Circuit Board
P-POD – Poly Picosatellite Orbital Deployer
LEO – Low Earth Orbit
NF – Noise Figure
LO – Local Oscillator
PLL – Phase Lock Loop
NRZI – Non Return to Zero Inverse
SMA – SubMiniature Version A (50Ω connector, DC-18 GHz)
SMB – Sub Miniature version B (50Ω connector, DC-4 GHz)
RBF – Remove Before Flight
RF – Radio Frequency
RFID – Radio Frequency Identification Device
RSSI – Received Signal Strength Indication
Rx/Tx – Receive/Transmit
TVAC – Thermal Vacuum Chamber
SNR – Signal to Noise Ratio
SRD – Short Range Device
UHF – Ultra High Frequency
U.FL – Miniature RF connector

VHF – Very High Frequency
VNA – Vector Network Analyzer